S
697.78
N7shp
1980

RENEWABLE ENERGY REPORT LIBRARY

PLEASE RETURN

STATE DOCUMENTS COLLECTION

APR 3 1984

MONTANA STATE LIBRARY
1515 E. 6th AVE.
HELENA, MONTANA 59620

SOLAR HEATING SYSTEM PERFORMANCE MONITORING

Prepared for

MONTANA DEPARTMENT of NATURAL RESOURCES and CONSERVATION

MONTANA STATE LIBRARY
S 697.78 N7shp 1980 c.1 Fowlkes
Solar heating system performance monitor
3 0864 00047532 0

SOLAR HEATING SYSTEM PERFORMANCE MONITORING

Prepared by

Charless Fowlkes
30 Gardner Park Drive
Bozeman, MT 59715

June, 1980

Prepared for

Montana Department of Natural Resources and Conservation
32 South Ewing, Helena, Montana 59620
Renewable Energy and Conservation Program
Grant Agreement Number 088-772

Available on loan from

Montana State Library, 1515 East Sixth Avenue
Justice and State Library Building, Helena, Montana 59620

This report was prepared under an agreement funded by the Montana Department of Natural Resources and Conservation. Neither the Department, nor any of its employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information apparatus, product, or process disclosed, or represents that its use would not infringe on privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Natural Resources and Conservation or any employee thereof. The reviews and opinion of authors expressed herein do not necessarily state or reflect those of the Department or any employee thereof.

THERMAL PERFORMANCE
OF THE FOWLKES SOLAR HOUSE

by

Charless W. Fowlkes

FOWLKES ENGINEERING
31 Gardner Park Drive
Bozeman, MT 59715

for

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
RENEWABLE ALTERNATIVE ENERGY SOURCES PROGRAM

John Orndorff, Bureau Chief

NOTICE

This report was prepared as an account of work sponsored by the Energy Division of the Montana Department of Natural Resources and Conservation through the Alternative Renewable Energy Sources Program. Neither the State of Montana, nor the Department, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

ABSTRACT

This project is a passive, water-wall design having movable insulation and wood auxiliary heat. The house is located about three miles south of Bozeman, Montana. The performance of the house was monitored from December 1978 through early March 1979. The ambient temperatures were abnormally low producing 27 percent higher heating degree days.

During the monitoring period, the sun provided 65 percent of the heat load and the average house temperature was 19°C (66°F). The wood furnace provided 20 percent and electrical dissipation in appliances provided 15 percent of the heat requirements. The collector typically operated at efficiency greater than 60 percent. The solar system provides over 70 percent of the heat requirements on an annual basis and about one cord of pine is used for auxiliary heat.

The disadvantages of this design are the daily temperature variations, average 6.4°C (12°F), and the manual operation of the insulating curtain and the auxiliary furnace. The house must be occasionally vented during September and October to prevent overheating.

NOTE ON UNITS

The data is presented in metric units. These units are in accord with the recommendations of the International Solar Energy Society as well as most current technical journals. The overall summaries and numbers in the text have been given in dual units. The heat load calculations are presented in conventional units.

Most readers are familiar with the Celsius or Centigrade temperature scale and are also familiar with energy units of kilowatt hours. The only other metric unit which occurs frequently in this report is the Joule (J), the metric unit of energy which replaces the Btu (a Btu is equal to 1,055 Joules). The mega joule (MJ) is equal to 10^6J (100,000 Btu/hr = 105 MJ/hr).

Other abbreviations used in this report include: m = meters; m^2 = square meters; l = liters; h = hours; gph = gallons per hour; and MBtu = millions of Btu's.

TABLE OF CONTENTS

1.0 Introduction 1
2.0 Description of House 1
3.0 Solar Collector 1
4.0 Auxiliary Wood Furnace 2
5.0 Heat Load 2
6.0 Transducer Arrangement 3
7.0 Hourly Performance 4
8.0 Explanation of Hourly Data Tables 4
9.0 Weekly Summary Data 5
10.0 Performance Summary During Monitoring Period 6
11.0 Projected Annual Performance 7
12.0 Summary 7

TABLES

Table 1 - Calculated Heat Load, Passive House 9
Table 2 - Sample Hourly Performance Summary 10
Table 3 - Passive House Performance Summary 11

FIGURES

Figure 1 - Fowlkes Passive House Photographs 12
Figure 2 - Photographs of the Passive Storage Wall 13
Figure 3 - Auxiliary Heating System Photographs 14
Figure 4 - Floor Plan for Ground Floor 15
Figure 5 - Floor Plan for Second Floor 16
Figure 6 - Shading Diagram, Passive House 17
Figure 7 - Section View and Transducer Layout 18
Figure 8 - Solar Wall Transducer Locations 19
Figure 9 - Furnace Outlet Duct Velocity Distribution 20
Figure 10 - Hourly Heat Balance Equation 21
Figure 11 - Computer Program of Energy Equations 22
Figure 12 - Hourly Temperatures During A Week In January 23
Figure 13 - Daily Energy Summary From January 4 - January 10 24
Figure 14 - Hourly Temperatures During A Week In March 25
Figure 15 - Daily Energy Summary From February 28 - March 6 26

Appendix I - Hourly Performance Data

1.0 INTRODUCTION

The passive solar house is located in Bozeman, Montana. This passive house was designed and built by Charless Fowlkes during 1976-77 and it has been occupied by him and his family since September 1977. The design is described as a "passive solar water wall" and the auxiliary heat is supplied by a wood-burning furnace. The solar heating system is integrated into the design and construction of the house.

2.0 DESCRIPTION OF HOUSE

A photograph of the house and the passive solar collector is shown in Figure 1. The house is a two-story wood-framed structure with a usable floor area of about 190 m^2 (2100 ft^2). The walls are framed with 5 x 15 cm (2 x 6 in) studs on 60 cm (24 in) centers and the roof is spanned by 5 x 25 cm (2 x 12 in) purlins. The walls and the floor are insulated with 15 cm (6 in) thick glass fiber batts and the roof with 25 cm (12 in) thick batts. A continuous vapor barrier of polyethylene was used inside all insulated surfaces.

Fenestration, excluding the collector glazing, is 12 percent of the floor area and all windows are double glazed. Electricity is used for lighting, hot water and all appliances.

3.0 SOLAR COLLECTOR

Radiation enters a vertical, double-glazed aperture which faces due south. The total area of the aperture is 43.6 m^2 (474 ft^2). The center 4 m^2 (43 ft^2) is not backed by the solar wall and serves as a window. The solar wall consists of 20 vertical tubes filled with water. The tubes are filament wound FRP, 40 cm (16 in) in diameter, 5.2 m (17 ft) long and contain 674 kg (1482 lb) of water each. The total storage mass of the wall is about 13,480 kg (30,000 lb). The tubes are painted flat green on the portion facing the sun and are spaced 3.5 cm (1.5 in) apart. Heat is transferred from the solar wall to the house by natural convection and radiation.

Design calculations indicated that a movable insulation system would be needed to control the heat loss through the collector glazing at night. The insulation system selected for this house consists of two thick fabric curtains which resemble window shades, Figures 1 and 2. The curtains are mounted on a common shaft and actuated by a geared electric motor. The outside of the curtain was fabricated from 6 ounce white, dacron sailcloth and

the inside from 6 ounce nylon pack cloth having a urethane coating. The insulation consists of four layers of 10 ounce Polarguard, a continuous polyester fiber. The thickness of the curtain is about 12 cm. Sewn along both vertical edges of the curtain is a bolt rope which runs in a continuous plastic guide attached to the window frame to minimize heat loss by convection around the edges.

4.0 AUXILIARY WOOD FURNACE

The auxiliary heat is supplied by a wood-burning furnace, Figure 3. The hot air from the furnace is normally directed to the solar storage wall. The furnace always operates at full output with the storage wall acting to moderate the amount of furnace heat entering the house itself.

The furnace consists of a fire box and a heat exchanger. It was designed by the author and fabricated from 11 and 13 gauge steel sheet. The fire box is lined with fire brick and is a base burning design. Preheated air enters the combustion chamber through three adjustable vents. The combustion gases leave the fire box below the grate and pass through a heat exchanger. A draft induction fan is used when starting a new fire. Heat is moved from the furnace to the solar wall with an air loop powered by a conventional furnace blower and thermostat. The only hot air outlets to the house are at the base of the solar storage wall. The cold air returns from a manifold located on the other side of the solar wall.

If the house temperature drops to around 15°C (60°F) and cold and cloudy weather is predicted, a fire is built. The fire box is filled with about 75 kg (165 lb) of pine and ignited. The furnace reaches full output during the next half hour and burns for about six hours. A second load of fuel is sometimes added to the fire box in extreme weather.

A floor plan of the house is shown in Figures 4 and 5. Note that the shop, pantry and garage attached to the north side of the house are not heated and thus do not enter the heat load measurements.

5.0 HEAT LOAD

The calculated heat load is shown in Table 1. Note that the large expanse of glass has an important effect on the heat load calculations. Because of this fact, the heat load is calculated with the insulating curtain open as well as closed. The curtain is closed primarily at night and open during the day. It is possible to calculate a weighted average heat load

by taking into account average ambient temperatures when the curtain is open and closed. This weighted average is also shown in Table 1.

The shading diagram taken 1.5 m (5 ft) above ground for the passive solar collector is shown in Figure 6. The morning shading is due to a mountain range to the east and the afternoon shading is due to trees west of the house. There is a minimum of shading at this site.

6.0 TRANSDUCER ARRANGEMENT

The transducer layout is shown in Figure 7. A total of 27 temperature probes were used. The house temperature was monitored at two locations upstairs and two locations downstairs. This was necessary due to the stratification of the air in this system. The ambient temperature, shop temperature and crawl space temperature were also measured.

Four sets of three temperature probes were immersed in the water in the centers of the heat storage tubes. These probes were placed at varying levels in an attempt to compensate for stratification and to arrive at an average storage temperature, Figure 8. The temperature change in the tubes is on the order of 1°C per hour while a temperature differential of 5°C may exist between the top and bottom of a tube at any given time. Analysis of the data showed that short-term, average power calculations were noticeably affected by the location and number of temperature samples. Daily average power calculations were relatively independent of the probe locations.

The solar transducer was positioned behind the glazing in the center of the solar wall to measure actual solar radiation input to the storage wall, Figure 7. Electric power input was monitored by measuring the current in the input mains with a clamp-on ammeter. This transducer is calibrated on-site using a watt meter and has an accuracy of at least 3 percent. The status inputs used a switch or relay to record the status of the furnace fan and the insulating curtain.

The furnace output was determined from the temperature difference in the supply and the return air ducts and the flow rate, Figure 9. The accuracy of this measurement is about 10 percent. Air leaks located beyond the measurement station could further increase the uncertainty of the actual furnace power input. The weight of wood burned in the auxiliary furnace was determined to within 5 percent.

7.0 HOURLY PERFORMANCE

The data system was in the house from November 28 to March 6. During this period 2,020 hours of average data were recorded for 19 individual channels. The total data lost in this period was 14 percent, due primarily to one bad cassette tape in mid-February. The total channel samples during the test were about 25,000,000.

The hourly performance was summarized using the heat balance equation shown in Figure 10. The terms on the left hand side of the equation were evaluated using the hourly data and formatted by the computer into hourly and daily summaries.

The solar input consisted of two terms: the solar radiation striking the tubes when the insulating curtain was up and the solar radiation entering the remainder of the glazing as simple passive gain.

The electric power dissipated into the house was estimated as an average of 0.6 times the total electric consumption. This factor is less than one due primarily to drain losses in the electrically-heated domestic hot water and an external vent on the electric clothes dryer.

The mass of the storage wall was known to within 5 percent and its temperature was measured by the internal probes. The thermal mass of the house was estimated by taking into account the sheetrock, some of the structural wood and the contents. The temperature of this mass was assumed to be equal to the average temperature of the house air.

The hourly values of stored heat changes would have been more accurate if there had been a larger sample of tube temperatures. The hourly change of temperature is small compared to variations existing within a single tube as well as variations between tubes. This shows up as fluctuations and phase lag in the calculated, stored heat values. Analysis of the data, however, showed that these hourly fluctuations average out and that the daily changes seem accurate and reliable. The equations used to form the hourly summary are given in Figure 11.

8.0 EXPLANATION OF HOURLY DATA TABLES

Look at Table 2 for January 1, 1979 as an example. The first column is solar insolation in MJ/m^2. The next six columns are the terms of the energy balance equation of Figure 10 and the units are mega joules (MJ). The TUBE STORED HEAT and HOUSE STORED HEAT are positive when they are absorbing heat and negative when they are delivering heat to the house. The

record starts at midnight and the temperature of the storage wall is dropping about 0.4°C (0.7°F) each hour and delivering around 20 MJ/hr to the house. The ambient temperature drops to -26.5°C (-15.7°F) at 3 AM. The house temperature is also dropping and the thermal mass of the house is delivering a few MJ each hour. The house reaches a minimum temperature of 13.5°C (56.3°F) at 9 AM. The sun strikes the collector and the insulating curtain is opened around 10 AM (see SOLAR TUBE HEAT).

The house temperature increases during the day and reaches a maximum of 21.3°C (66°F) at 3 PM, just before sunset. The tubes absorb heat during the day until 4 PM, then they start delivering heat to the house through the evening and night.

The hourly heat loss factor is calculated by adding together the inputs of the heat balance and dividing this by the temperature difference between the inside and outside of the house. These values are shown in the CALC LOSS FACTOR column. It is clear that the loss factor increases when the insulating curtain is up during the day. The HOUSE TEMP DIFF column is the difference in temperature between the upper and lower floor due to stratification. The HOUSE TUBE DIFF column is the storage tube temperature minus average house temperature. The ambient temperature, AMBNT TEMP, reached a high of -17.6°C (0°F) this day.

The bottom row of numbers is the daily summary and is the sum of all energy items and the average of the temperatures. The solar total input was 504 + 156 or 660 MJ. The electric input was 114 MJ and the tubes had a 24-hour net energy loss of 32 MJ.

Appendix I contains a sample of 52 days of hourly data, about half of the data bank. The format of this data is the same as discussed in the previous example. This data describes the behavior of the house during a variety of environmental conditions.

9.0 WEEKLY SUMMARY DATA

Some hourly data for a very cold but sunny week in January is plotted in Figure 12. The solid curves are solar insolation and the dotted curves are ambient temperature, house temperature and tube temperature. Note that all temperatures respond to the sun. The solar house, however, maintains an equilibrium temperature some 45°C (80°F) above the ambient temperature early in the week. For the first five days the house is heated entirely by the sun. On the sixth day there is little solar radiation and the auxiliary furnace is

fired, some of the heat being stored in the tubes. The last day of the week also has little radiation and the house uses stored heat from the tubes.

Figure 13 shows a bar graph of the daily energy use and distribution during this week of January 4 to January 10 discussed previously. The top of the bar graph represents the total heat dissipated by the house during the 24-hour period beginning at midnight. The top bar element represents electrical input and the shaded area represents total solar input. The last element represents total stored energy. If this element lies below zero, there was a net gain in stored energy. Average house and ambient air temperatures are plotted; the bars show the daily extreme values.

During the first five days of this very cold week, the sun was meeting the heat load but the net stored energy was relatively small. Auxiliary wood heat was required on the sixth day, which was overcast. The following day was also overcast; heat was supplied to the house from the storage wall. (The auxiliary furnace is in the basement which stores heat that is not included in the heat balance and reduces the apparent heat load on this day.)

Figure 14 shows the hourly temperature variations and solar insolation for the first week in March. There were only two days in the middle of the week that were clear. Figure 15 depicts the corresponding thermal behavior during this period. Heat stored during two clear days at mid-week is sufficient to carry the heat load for the next three partially overcast days because the ambient temperatures are moderate.

Note that the largest temperature swings occur on very cold, clear days. Since heat is transferred from the storage wall to the house by natural convection, this limit on the rate of heat transfer results in a lower minimum house temperature. The higher maximum is due to direct solar gain.

10.0 PERFORMANCE SUMMARY DURING MONITORING PERIOD

Hourly data was recorded between November 28 and March 6. A summary of this entire period is shown in Table 3. The heating degree days during the test period were 27 percent above average creating a challenging test environment. The overall average house temperature was 19.0°C (66°F) with an average differential of 3.7°C (6.6°F) between the upper and lower floors. The average daily swing in house temperature was 6.4°C (11.5°F).

During the test period, electrical power dissipated in the house was 7.7 GJ (8×10^6 BTU). Thirteen fires were built in the auxiliary wood furnace which put a total of 10.3 GJ (10.9×10^6 BTU) into the house (about

0.8 cord of pine was consumed). The total heat requirement of the house was 52 GJ (55×10^6 BTU) based on the experimental heat loss factor of 0.83 $MJh^{-1}{}^{o}C^{-1}$ (486 $BTUh^{-1}{}^{o}F^{-1}$). Based on these measurements, the sun provided 34 GJ (36×10^6 BTU) or 65 percent of the total heating energy during December, January and February.

The average efficiency of the furnace was determined by weighing the total wood put in during each firing and then measuring inlet and outlet duct temperatures and outlet flow rate. The heating value of the wood was taken as 18.4 $MJkg^{-1}$ (8,823 $BTUlb^{-1}$). Using these data, the average overall efficiency of the wood furnace was 58.7 percent during eleven test firings.

11.0 PROJECTED ANNUAL PERFORMANCE

During the entire heating season, a total of sixteen fires were built in the auxiliary wood furnace, the first on November 11 and the last on January 27. A total of 1140 kg (2508 lb, about one cord) of wood was burned producing about 12.7 GJ (13.4×10^6 BTU) of heat. The annual electric power, dissipated as heat into the house, contributed about 15 GJ, or 16×10^6 BTU (700 $kWh\ mo^{-1}$). Using an annual value of 5000°C days, the heat load of the house would be 99.6 GJ (105×10^6 BTU) and the annual solar fraction, 72 percent. This summary data is also given in Table 3.

12.0 SUMMARY

The test results show that this system provides a high percentage of the house heat load by solar conversion, even during extremely cold weather. It seems unlikely that the overall solar fraction could be significantly improved by economically admissible changes in either aperture area or storage capacity. The conversion efficiency of the wood furnace and the heat loss factor of the house itself could not be greatly improved.

Reductions of over 10 percent in the overall heat loss would result if the movable insulation could be constructed so as to have a heat transfer coefficient equivalent to a normal wall. The effective insulating value of the curtain is about R-5. The curtain is currently opened and closed by a manual switch. The curtain would need an automatic control to make this system acceptable for general use. The furnace is not automatic and this is another inconvenience. A reduction in the 24-hour temperature variations would increase the comfort of the house. This is a difficult and fundamental problem of passive design.

Condensation between the curtain and the window is a problem and may eventually cause the wood sills to deteriorate. The insulating curtain shows signs of wear and will need to be periodically repaired and maintained.

TABLE 1

CALCULATED HEAT LOAD, PASSIVE HOUSE

	R	U (Btu/hr ft^2 $^\circ$F)	Area (sq. ft.)	U X A
Roof	40	.025	1112	28
Walls	20	.05	1660	83
Floor	40	.025	1144	29
Windows	1.4	.68	217	148
Skylights	2.7	.36	30	10.8
Aperture:				
(Open)	(1.4)	(.68)	(426)	(290)
Closed	7.4	.13	426	55

Infiltration ($\frac{1}{2}$ air change/hour - 20,592 ft^3)

20,592 ft^3 x $\frac{1}{2}$hr x .018 = 155

TOTAL HEAT LOAD:	(With Curtain Open)	744 Btu/hr$^\circ$F	1.4 MJ/hr$^\circ$C
	(With Curtain Closed)	509	.96
	Weighted Average	571	1.08

TABLE 2

Sample Hourly Performance Summary

DAILY PERFORMANCE SUMMARY FOR PASSIVE HOUSE (ID='II')

UNITS: ENERGY-MJ,TEMPERATURE-DEG C

CH	MO	DAY	HR	SOLAR INSOL (INT.)	SOLAR TUBE HEAT	SOLAR HOUSE HEAT	ELECT POWER (0.6)	WOOD FURNACE HEAT	TUBE-STORED HEAT	HOUSE-STORED HEAT	DEGREE HOURS (AVG)	CALC LOSS FACTOR	TUBES TEMP	AMBNT TEMP	HOUSE TEMP	HOUSE TEMP DIFF	HOUSE TUBE DIFF	
7	1	1	1	.0	.0	.0	2.3	.0	-19.6	-3.0	41.3	.6	24.8	-25.5	15.9	5.5	8.9	
8	1	1	2	.0	.0	.0	3.8	.0	-19.4	-3.0	41.2	.6	24.4	-25.7	15.5	5.3	8.9	
9	1	1	3	.0	.0	.0	2.2	.0	-19.8	-2.8	41.6	.6	24.1	-26.5	15.2	5.3	8.9	
0	1	1	4	.0	.0	.0	2.2	.0	-19.8	-2.8	40.7	.6	23.7	-25.9	14.8	5.2	8.9	
1	1	1	5	.0	.0	.0	1.7	.0	-19.4	-1.2	39.0	.6	23.3	-24.3	14.7	4.8	8.6	
2	1	1	6	.0	.0	.0	2.4	.0	-19.2	-3.0	37.8	.7	22.9	-23.5	14.3	4.9	8.6	
3	1	1	7	.0	.0	.0	1.4	.0	-18.4	-2.4	36.6	.6	22.6	-22.6	14.0	4.9	8.6	
4	1	1	8	.0	.0	.0	1.0	.0	-19.4	-1.9	35.6	.6	22.2	-21.9	13.8	4.8	8.5	
5	1	1	9	.0	.0	.4	1.0	.0	-18.5	-1.7	34.2	.6	21.8	-20.7	13.5	4.7	8.3	
6	1	1	10	.2	.0	2.2	1.0	.0	-18.2	-.2	32.4	.7	21.5	-19.9	13.5	4.7	8.0	
7	1	1	11	1.8	31.1	19.0	2.6	.0	-10.7	7.5	33.1	1.7	21.3	-18.7	14.5	5.4	6.8	
8	1	1	12	3.0	106.7	30.2	5.8	.0	33.5	22.5	35.6	2.4	21.9	-18.3	17.3	6.7	4.7	
9	1	1	13	3.2	114.3	32.4	9.0	.0	62.9	13.7	36.6	2.2	23.1	-17.6	19.0	7.8	4.2	
0	1	1	14	3.1	110.5	31.3	5.9	.0	71.8	10.8	38.2	1.7	24.5	-17.8	20.3	8.2	4.2	
1	1	1	15	2.7	94.0	26.6	7.1	.0	69.2	8.2	39.9	1.3	25.9	-18.5	21.3	7.8	4.5	
2	1	1	16	1.3	47.0	13.3	3.7	.0	46.8	-.6	41.2	.4	26.8	-19.9	21.3	7.1	5.5	
3	1	1	17	.1	.5	1.1	3.4	.0	-.9	-11.2	42.9	.4	26.7	-23.0	19.9	5.8	6.9	
4	1	1	18	.0	.0	.0	9.8	.0	-14.0	-4.0	46.0	.6	26.5	-26.7	19.4	5.4	7.1	
5	1	1	19	.0	.0	.0	14.2	.0	-16.1	-3.4	46.2	.7	26.2	-27.2	18.9	5.5	7.2	
6	1	1	20	.0	.0	.0	12.0	.0	-15.8	-3.6	45.3	.7	25.9	-26.9	18.5	5.2	7.4	
7	1	1	21	.0	.0	.0	7.1	.0	-15.9	-3.1	44.6	.6	25.5	-26.5	18.1	4.6	7.5	
8	1	1	22	.0	.0	.0	4.6	.0	-17.0	-3.2	43.4	.6	25.2	-25.7	17.7	4.3	7.5	
9	1	1	23	.0	.0	.0	6.0	.0	-17.7	-3.1	40.9	.7	24.9	-23.7	17.3	4.1	7.6	
0	1	2	0	.0	.0	.0	3.8	.0	-16.6	-3.5	40.5	.6	24.6	-23.6	16.9	4.1	7.7	
Y	1	1	24	15.6	504.1	155.5	114.3	.0	-32.4	4.8	954.9	.9	24.2	-22.9	16.9	5.5	7.7	SUM-AVG

TABLE 3

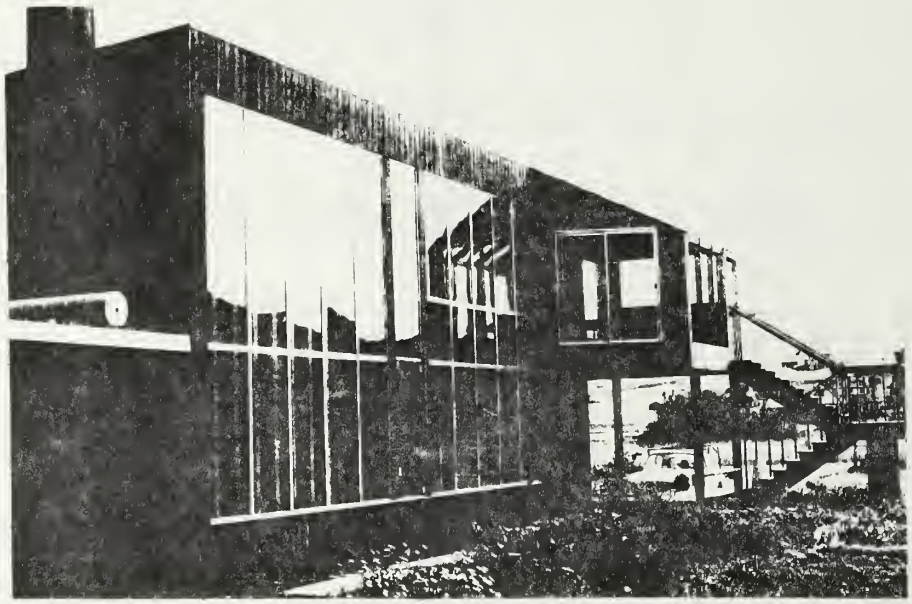
PASSIVE HOUSE PERFORMANCE SUMMARY

MONITORING PERIOD (December, January, February)			PROJECTED ANNUAL		
Average Temperatures	°C	°F			
House Temperature	19	66			
Ambient Temperature	-11	12	NO DATA		
Daily Temperature Swing	6.4	11.5			
Upstairs - Downstairs	3.7	6.7			

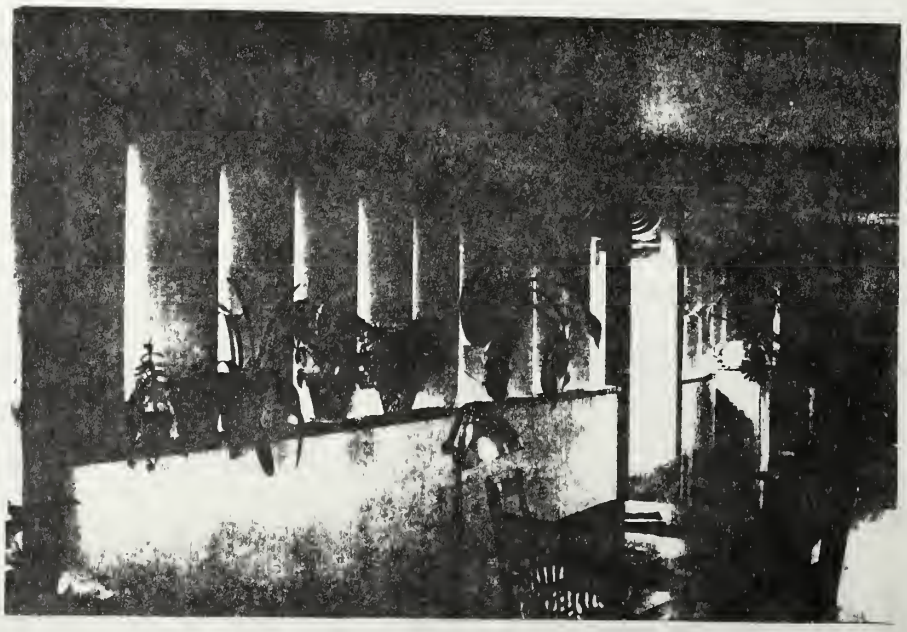
ENERGY QUANTITY	GJ	%	MBTU	GJ	%	MBTU
Heat Load	52	(100)	55	99.6	(100)	105
Solar Heat	34	65	36	71.9	72	76
Auxiliary Wood	10.3	20	11	12.7	13	13
Electricity	7.7	15	8	15	15	16

GJ = giga joules = 10^9 joules

MBTU = millions of Btu's = 10^6 Btu's

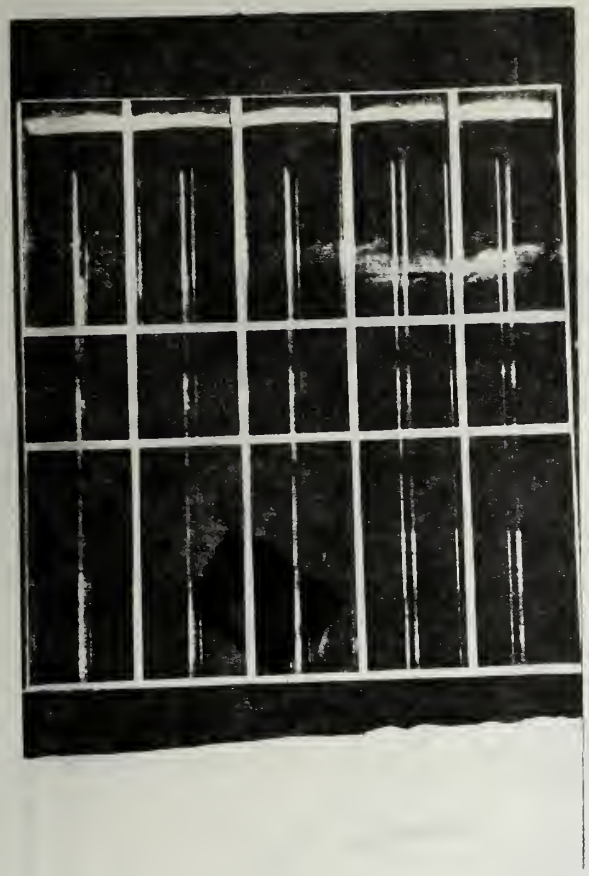


(a) External view showing solar collector glazing

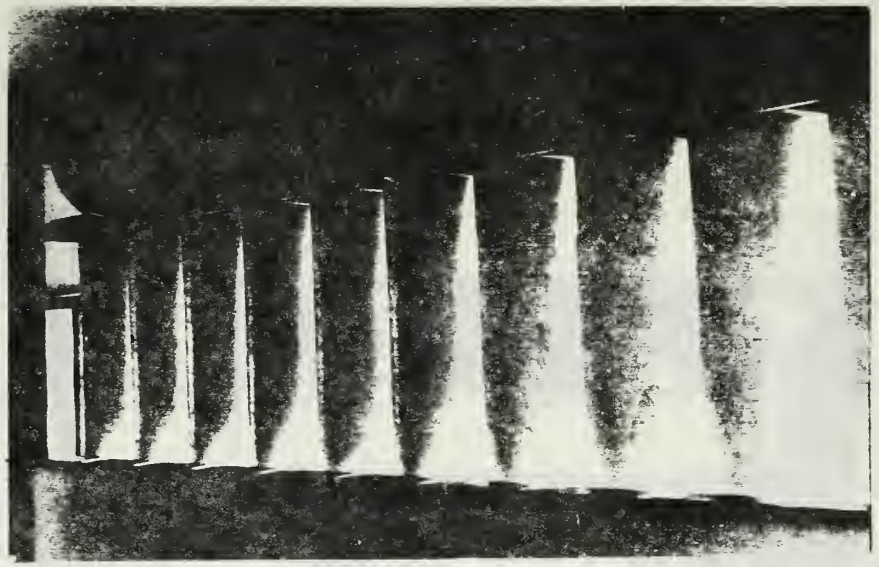


(b) Interior view showing insulating curtain and storage wall

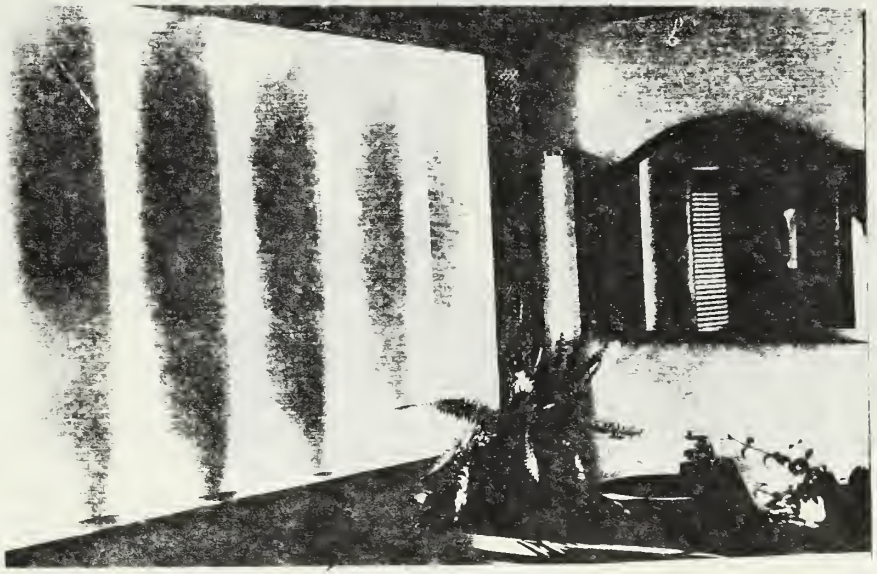
Figure 1: Fowlkes Passive House Photographs



(b) Half of solar collector showing tubes, solar window and furled insulating curtain.

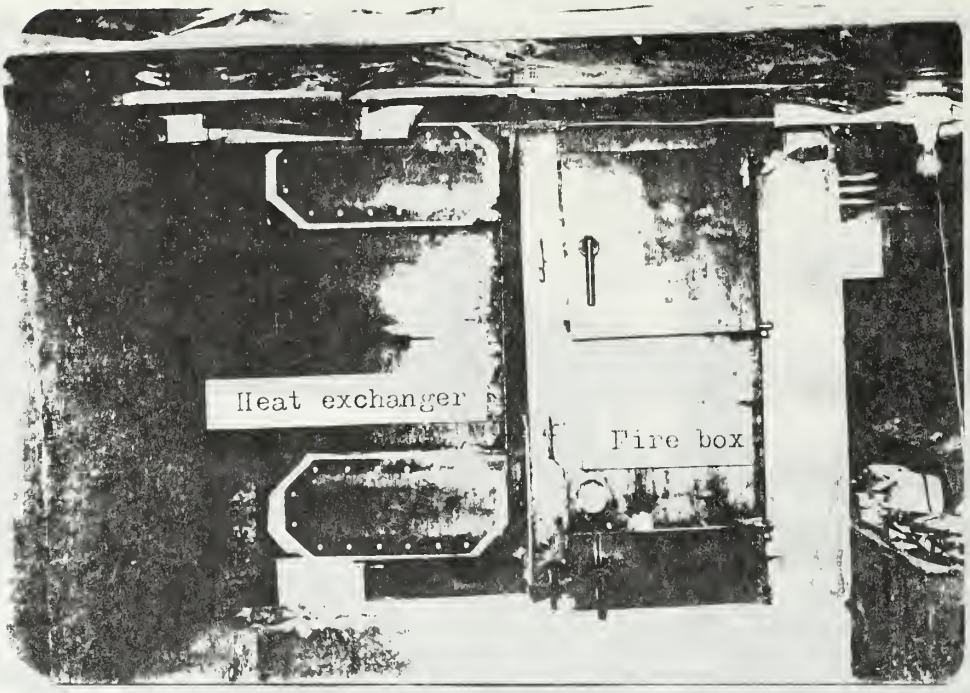


(a) Fiberglass tubes forming solar wall as seen from upper floor. Note rolled insulating curtain at top of photo.



(c) Solar wall as seen from lower floor dressing room.

Figure 2: Photographs of the Passive Storage Wall



(a) Auxiliary wood furnace

(b) Hot and cold air ducting to solar wall (before tubes)

Figure 3: Auxiliary Heating System Photographs

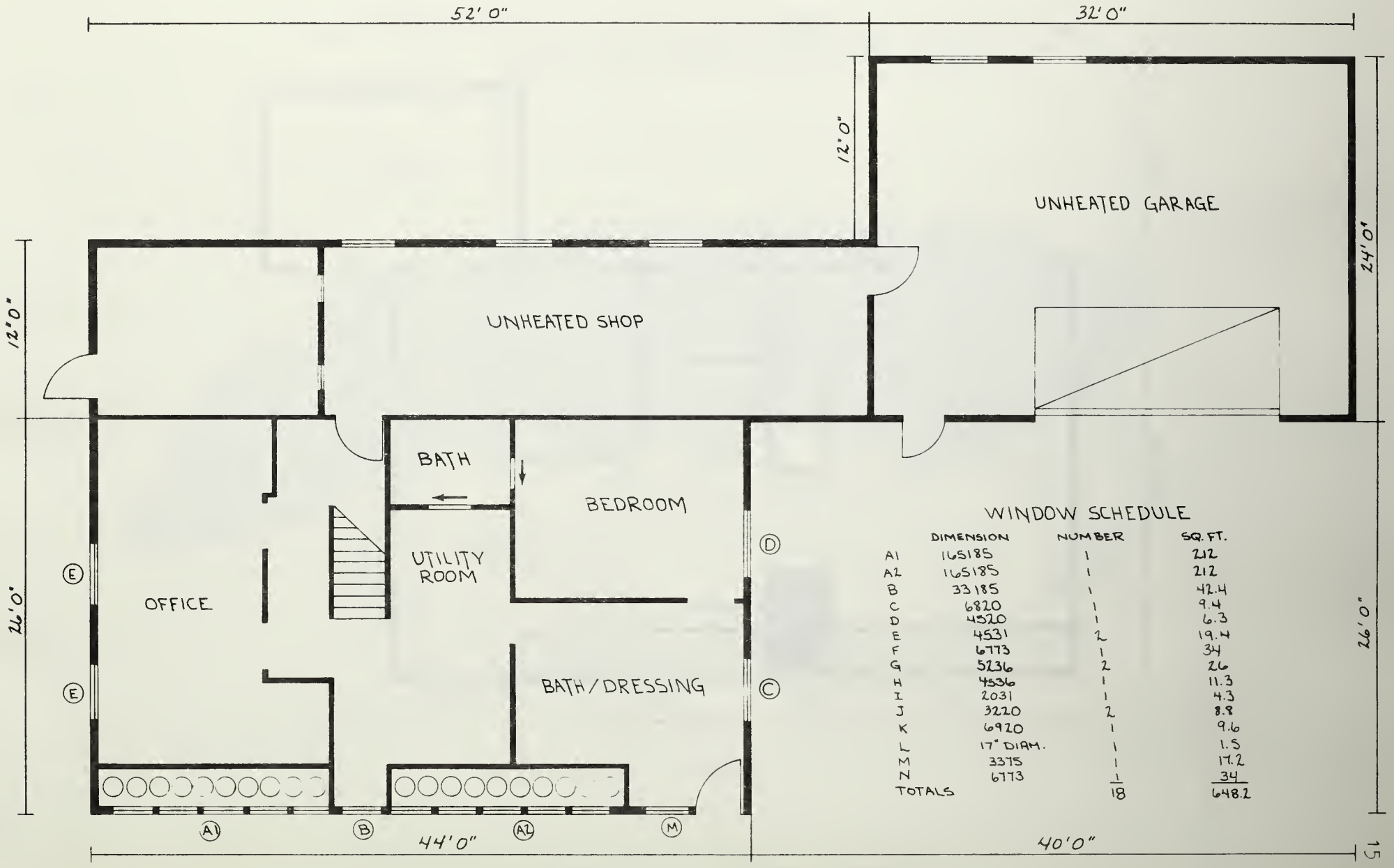


Figure 4: Floor Plan for Ground Floor

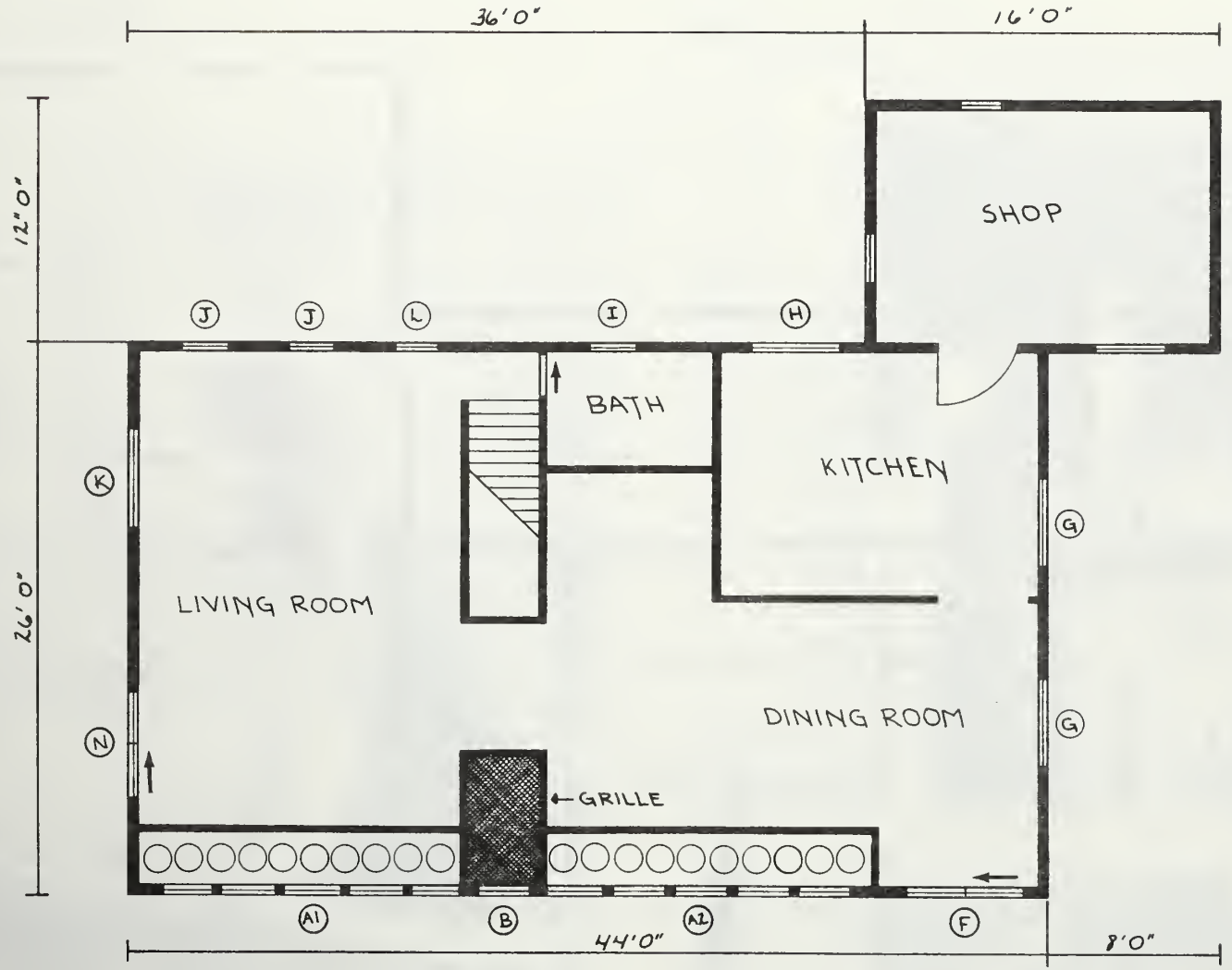


Figure 5: Floor Plan for Second Floor

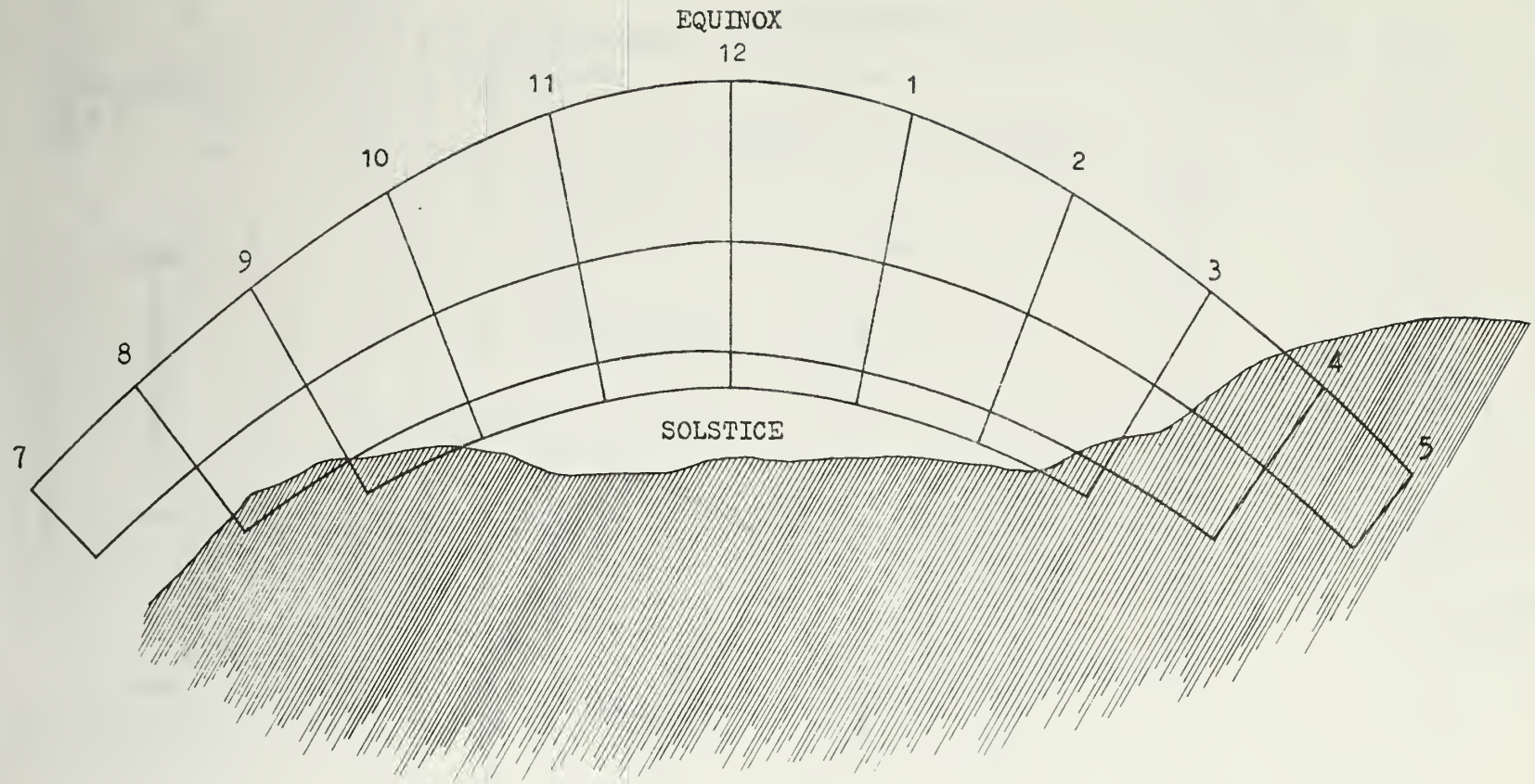


Figure 6: Shading Diagram Passive House

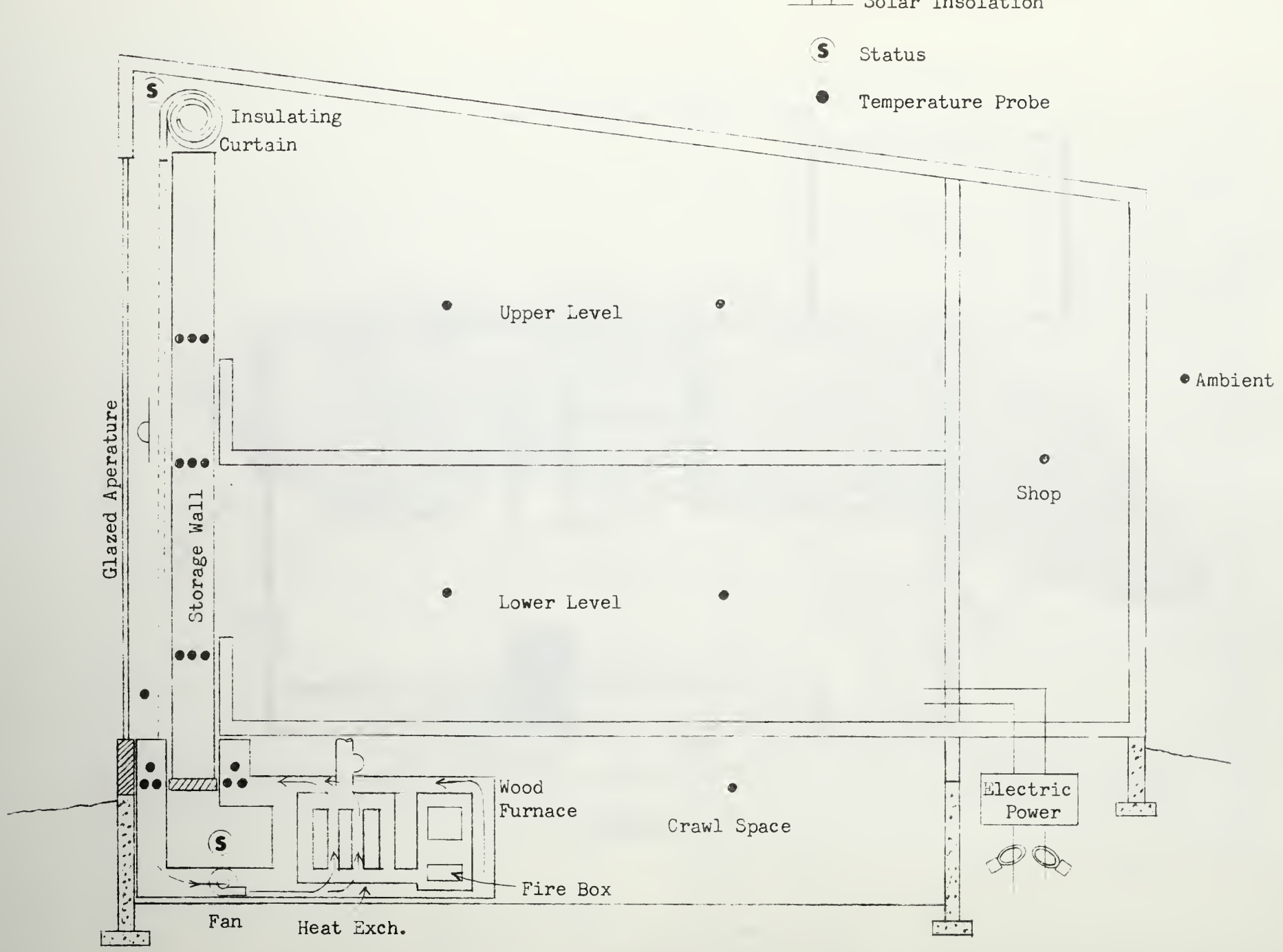


Figure 7: Section View and Transducer Layout

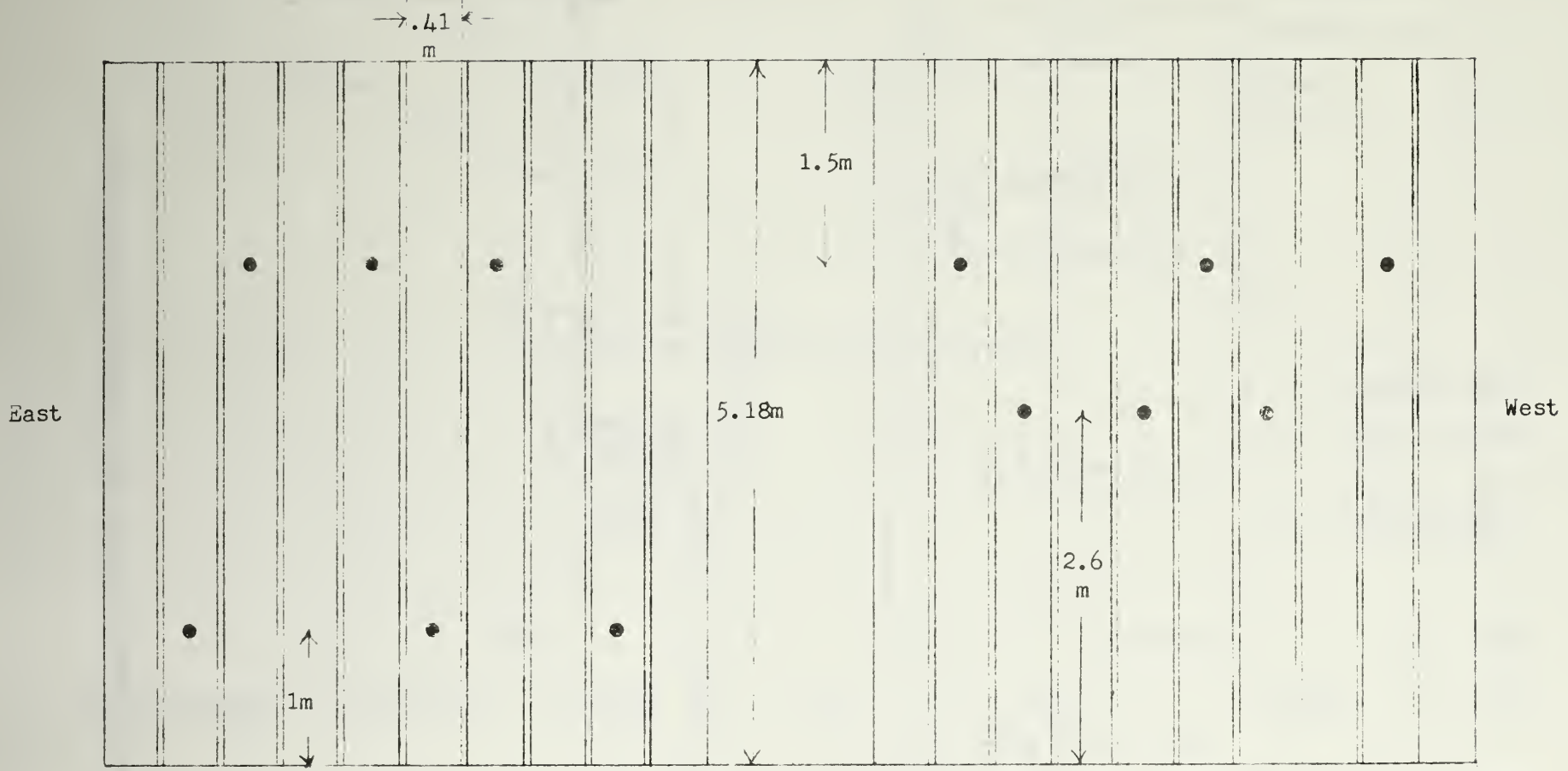
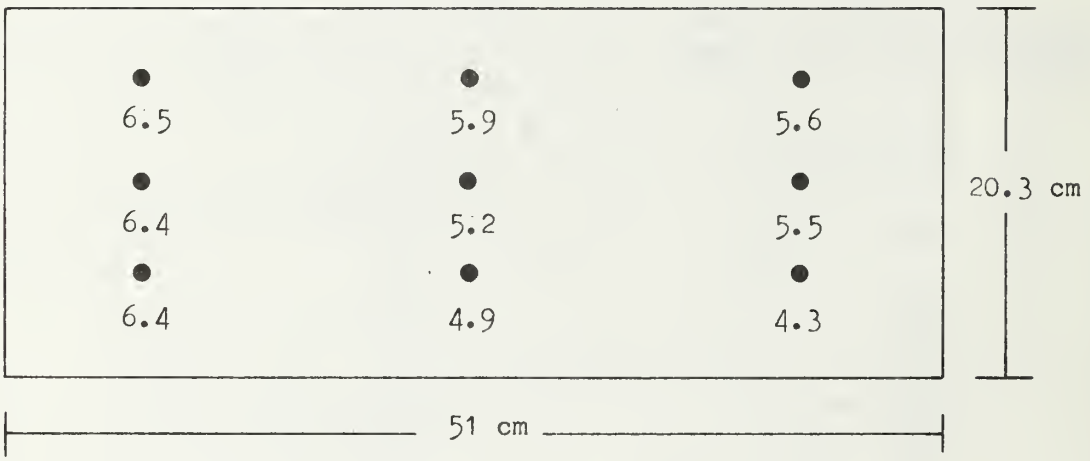


Figure 8: Solar Wall Transducer Locations

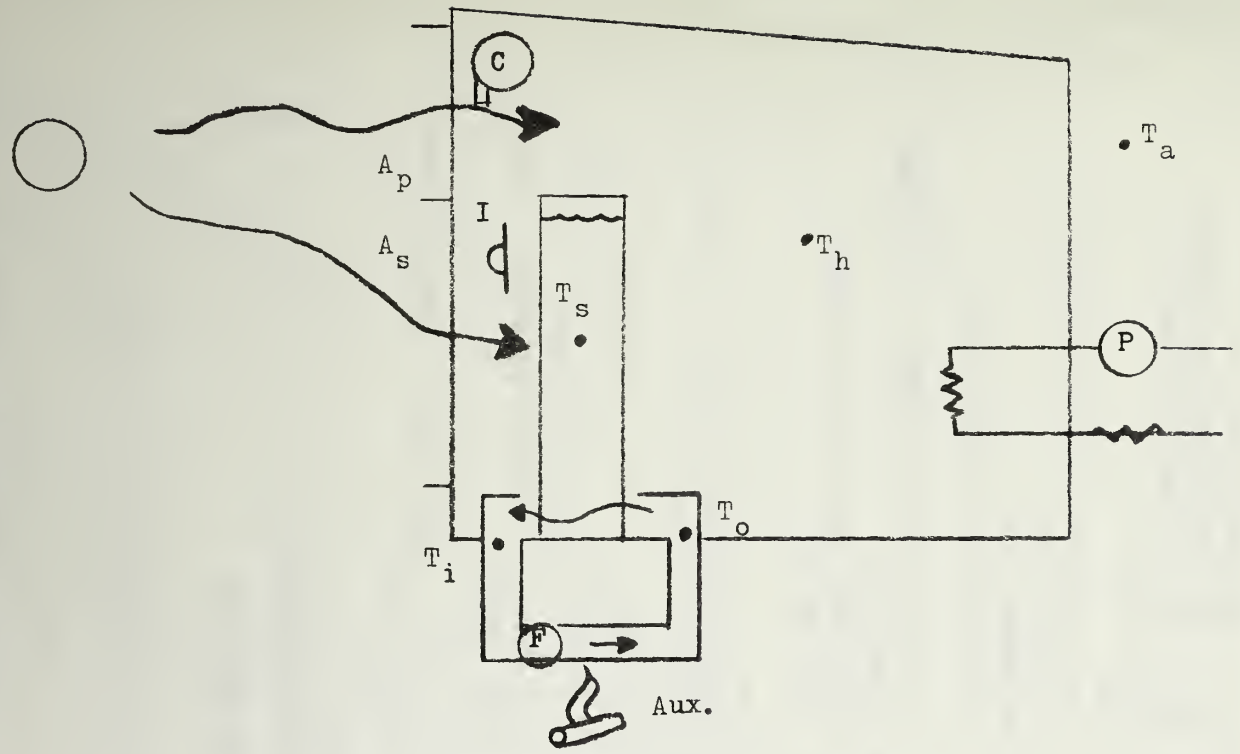
FURNACE OUTLET



Average Velocity = 5.63m/sec.

Volume Flow Rate = .581m^3/sec or Volume Flow Rate = 34.8m^3/min

Figure 9: Furnace Outlet Duct Velocity Distribution



Status:

Curtain up	C = 1
Curtain down	C = 0
Fan on	F = 1
Fan off	F = 0

m = mass

c = specific heat

A_p = area of passive glass

A_s = area of solar wall glazing

INPUT + Δ STORED = LOSS

SOLAR PASSIVE + SOLAR WALL + ELECTRIC + AUX. + ΔWALL + ΔHOUSE = LOSS

$$I A_p + I A_s C + 0.6 P + m c_p (T_o - T_i) F + m_w c_w \Delta T_w + m_h c_h \Delta T_h = \text{LOSS}$$

Figure 10: Hourly Heat Balance Equation

```
3000REM SUBR *** COMPUTE HOURLY SUMS
3005 !"-- SUMMING"
3010 N0=N0+1\REM #HRS
3015 S(1)=D(1)*3.6\ REM SOLAR INSOLATION INSIDE MJ PER SM
3020 S(2)=D(4)*D(1)*127.0\REM SOLAR-TUBE ENERGY
3030 S(3)=D(1)*36.0\REM SOLAR-HOUSE ENERGY
3040 S7  =(D(2)+D(3))*3.6\REM ELECT UTIL ENERGY
3050 S(4)=S7  *0.6\REM ELECT POWER HEAT
3060 S(5)=(D(7)-D(6))*D(5)*2.41\REM WOOD FURNACE HEAT,NEW CALIBRATION
3070 S(10)=(D(8)+2*D(10))/3\REM WEIGHTED AVERAGE TUBE TEMP,GOOD PROBES
3075 S(11)=D(19)
3080 S(12)=(D(12)+D(13)+D(14)+D(15))/4.0\REM HOUSE TEMP (AVG)
3085 S(13)=(D(12)+D(13)-D(14)-D(15))/2 \REM HOUSE UP-DOWN TEMPERATURE
3090 S(6)=(S(10)-S8   )*52.0\REM TUBE-STORED HEAT,NEW CONSTANT
3100 S(7)=(S(12)-S9   )*8.0\REM HOUSE-STORED HEAT
3110 S(8)=S(12)-D(19)\REM DEGREE-HOURS
3120 S(9)=(S(2)+S(3)+S(4)+S(5)-S(6)-S(7))/S(8)\REM HEAT LOSS FACTOR
3125 S(14)=S(10)-S(12)\REM TUBE MINUS HOUSE TEMP
3130 !#1,%3I,R,%4I,M0,%3I,D0,%5I,H0,TAB(15),
3140 FOR I=1 TO 14\T(I)=T(I)+S(I)\REM SUM FOR DAY, PRINT HR DATA
3150 !#1,%7F1,S(I),\NEXT\!#1
3160 S8=S(10)\S9=S(12)\RETURN   \REM SAVE FOR TEMP DIFFERENCE - TUBE&HOUSE
3200REM *** CALC AVERAGES & FINAL QUANTITIES
3210 FOR I=9 TO 14\ REM AVERAGE TEMPERATURES (NOTE HEATS NOT INCL.,)
3220 T(I)=T(I)/N0\REM DAILY AVGS = SUM / NR HRS
3230 NEXT\RETURN
3400REM SUBR *** PRINT REPORT HEADING
3405 !#1\!#1"  DAILY PERFORMANCE SUMMARY FOR PASSIVE HOUSE  (ID=",R$,")"
3406 !#1\!#1"  UNITS: ENERGY-MJ,TEMPERATURE-DEG C"
3410 !#1\!#1,"REC# MO DAY  HR ",TAB(16),
3420 !#1," SOLAR  SOLAR  SOLAR  ELECT  WOOD   TUBE-  HOUSE- DEGREE  CALC ",
3430 !#1," TUBES  AMBNT  HOUSE  HOUSE  HOUSE"
3440 !#1,TAB(16),
3450 !#1," INSOL  TUBE   HOUSE  POWER FURNACE STORED STORED HOURS   LOSS ",
3460 !#1, " TEMP   TEMP   TEMP   TEMP   TUBE "
3470 !#1,TAB(16),
3480 !#1," (INT.) HEAT   HEAT   (0.6)  HEAT   HEAT   HEAT   (AVG)  FACTOR",
3490 !#1, "                     DIFF   DIFF"
3495 RETURN
3500REM SUBR *** PRINT SUMMARY DATA
3510 !#1\!#1,"DAY",%4I,M1,%3I,D1,%5I,N0,TAB(15),
3520 FOR I=1 TO 14
3530 !#1,%7F1,T(I),\NEXT\!#1," SUM-AVG "\!#1
3540 RETURN
3550END
```

Figure 11: Computer Program of Energy Equations

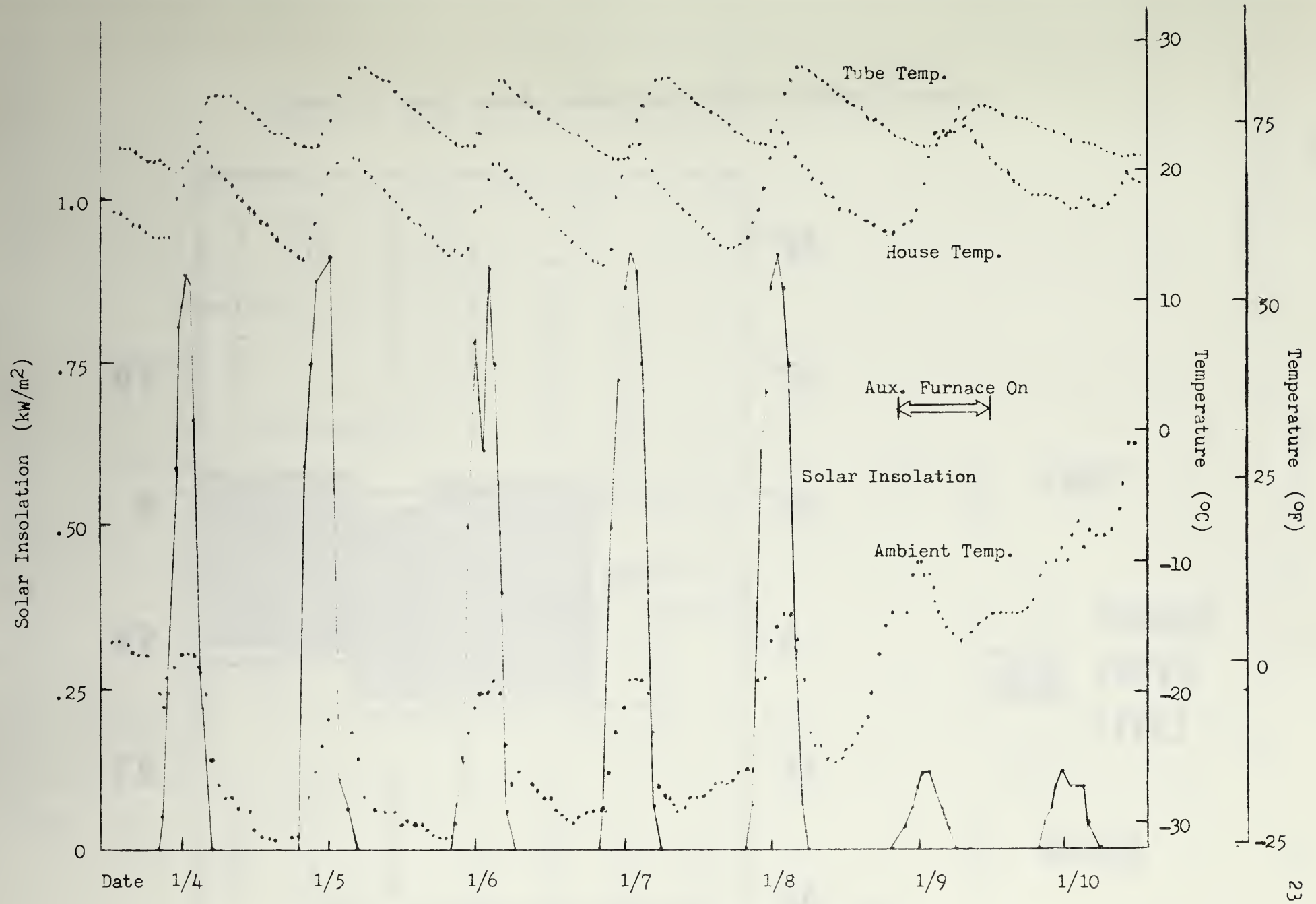


Figure 12: Hourly Temperatures During A Week In January

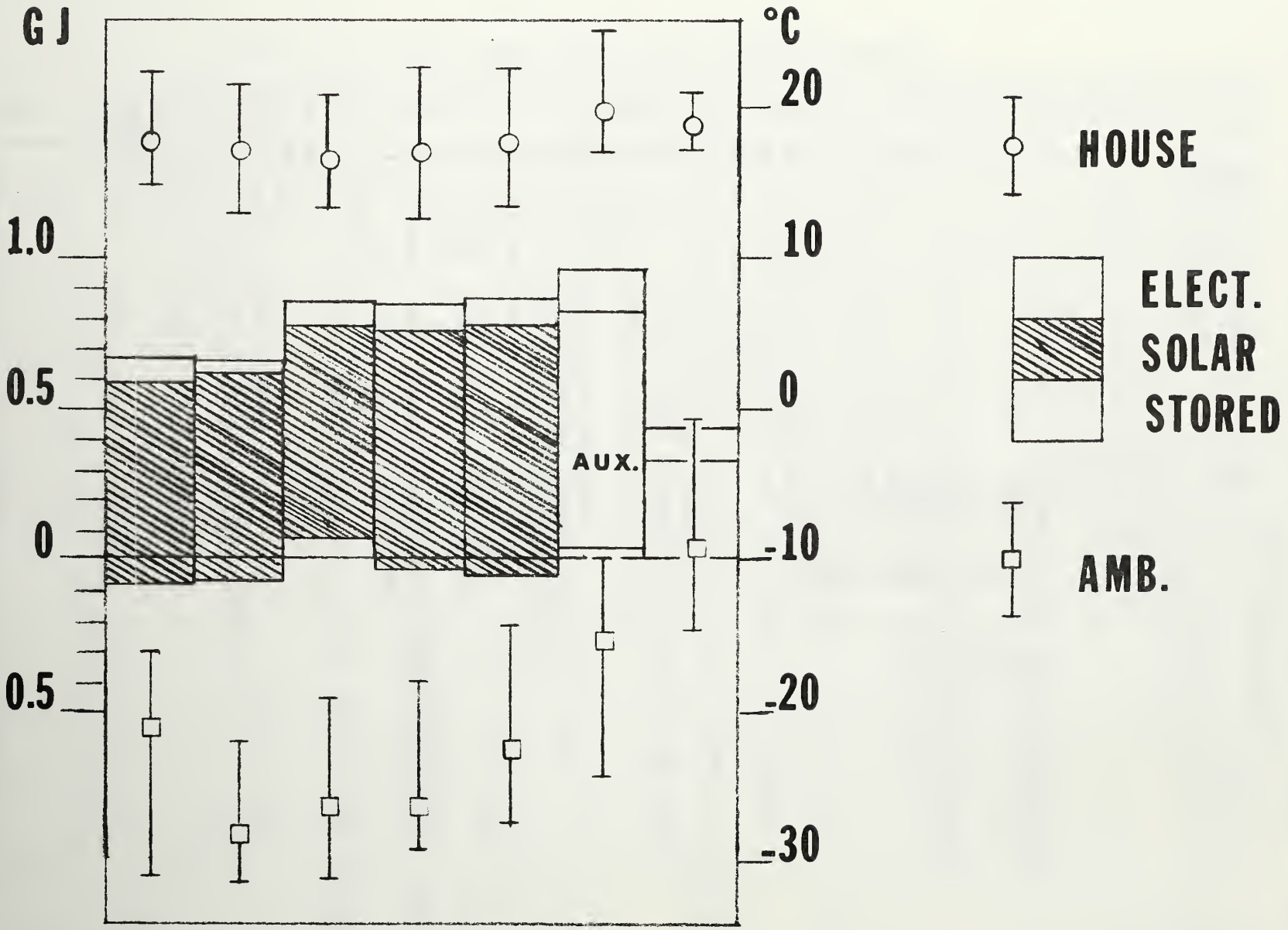


Figure 13: Daily Energy Summary From January 4 Through January 10

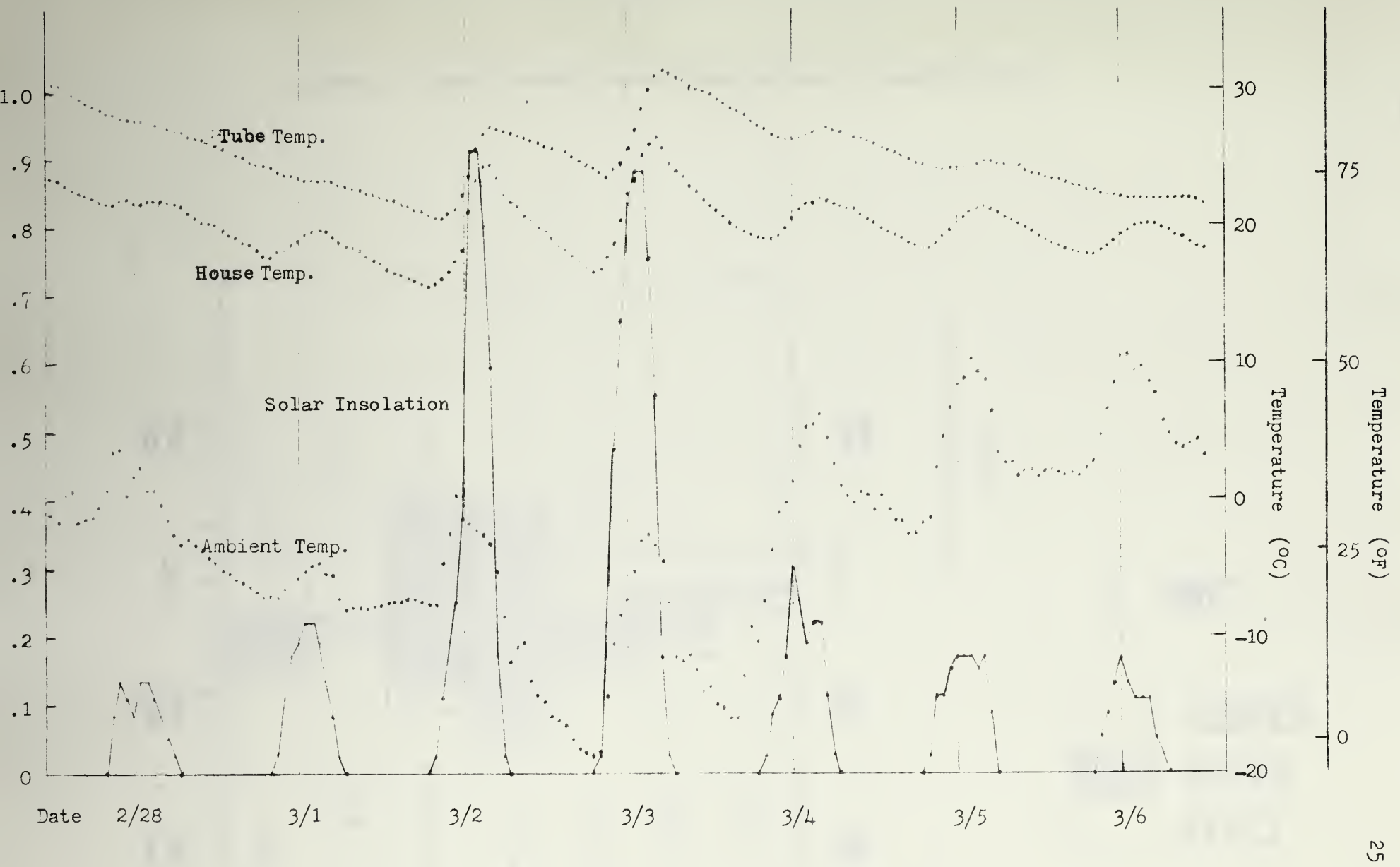


Figure 14: Hourly Temperatures During A Week In March

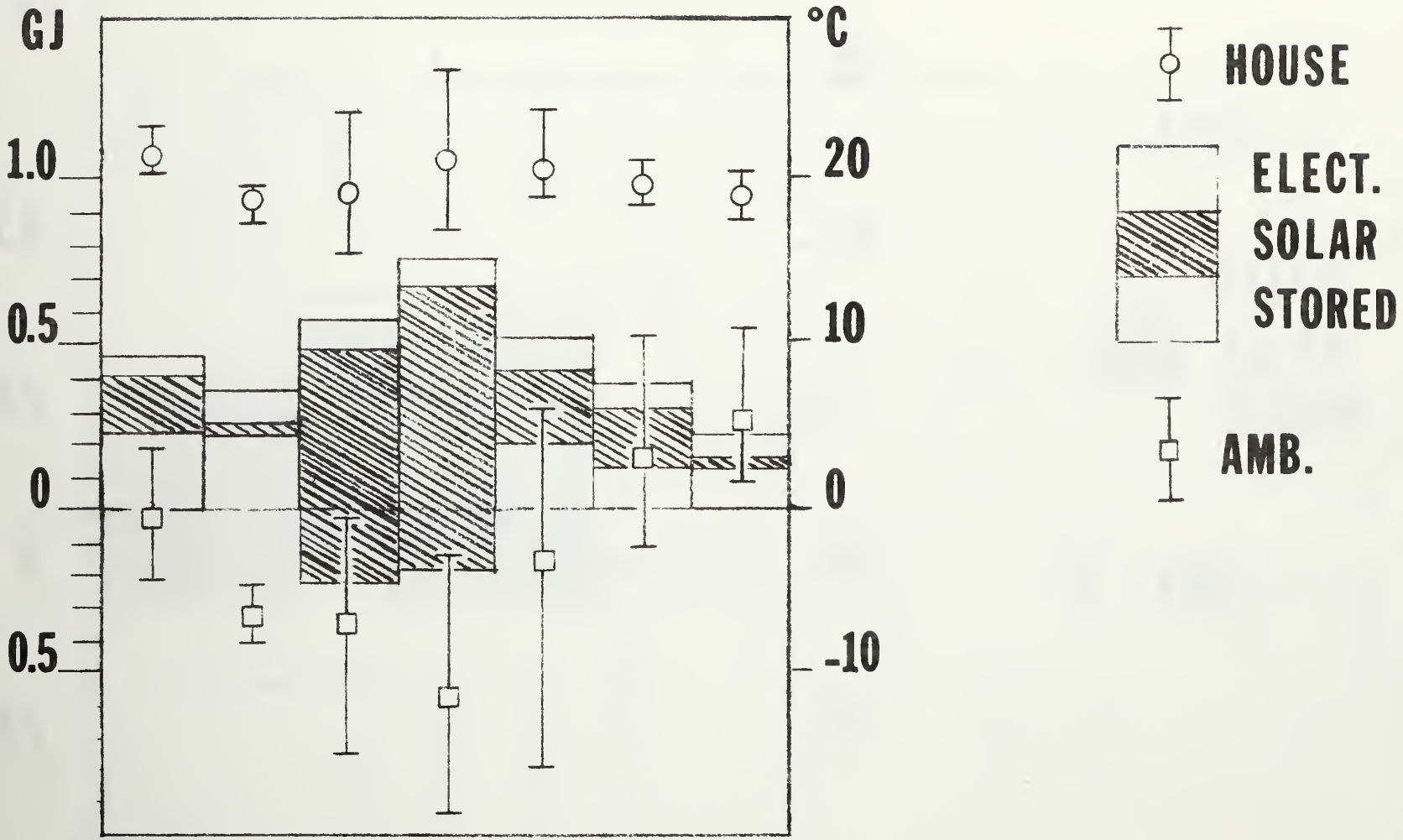


Figure 15: Daily Energy Summary From February 28 Through March 6

APPENDIX I

HOURLY PERFORMANCE DATA

Fowlkes Solar House

Appendix I - Hourly performance Data

Omitted with the exception of one (1) sample page

TABLE 1

DAILY PERFORMANCE SUMMARY FOR PASSIVE HOUSE (ID='II')

UNITS: ENERGY-MJ,TEMPERATURE-DEG C

REC#	MO	DAY	HR	SOLAR INSOL (INT.)	SOLAR TUBE HEAT	SOLAR HOUSE HEAT	ELECT POWER (0.6)	WOOD FURNACE HEAT	TUBE-STORED HEAT	HOUSE-STORED HEAT	DEGREE HOURS (AVG)	CALC LOSS FACTOR	TUBES TEMP	AMBNT TEMP	HOUSE TEMP	HOUSE TEMP DIFF	HOUSE TUBE DIFF	
1	12	29	3	.0	.0	.0	2.6	58.2			54.0		24.7	-31.3	22.7	.9	2.0	
2	12	29	4	.0	.0	.0	1.7	19.0	2.3	-10.6	52.9	.6	24.7	-31.6	21.4	.6	3.3	
3	12	29	5	.0	.0	.0	1.3	4.1	-4.7	-8.7	53.1	.4	24.6	-32.8	20.3	.6	4.3	
4	12	29	6	.0	.0	.0	1.0	.6	-8.7	-7.1	53.0	.3	24.4	-33.6	19.4	.6	5.1	
5	12	29	7	.0	.0	.0	2.6	.0	-11.3	-5.6	51.9	.4	24.2	-33.3	18.7	.7	5.5	
6	12	29	8	.0	.0	.0	1.4	.0	-12.1	-4.9	52.1	.4	24.0	-34.0	18.1	.9	5.9	
7	12	29	9	.2	.2	1.8	1.8	.0	-12.3	-3.3	52.0	.4	23.8	-34.3	17.7	.9	6.1	
8	12	29	10	1.6	57.2	16.2	3.9	.0	-3.8	3.6	49.9	1.6	23.7	-31.8	18.1	2.1	5.6	
9	12	29	11	2.4	86.4	24.5	1.1	.0	25.8	12.5	48.6	1.5	24.2	-28.9	19.7	3.9	4.5	
10	12	29	12	3.0	104.1	29.5	6.0	.0	51.1	13.2	47.9	1.6	25.2	-26.6	21.3	5.3	3.8	
11	12	29	13	3.2	111.8	31.7	1.4	.0	70.0	11.0	47.7	1.3	26.5	-25.0	22.7	5.9	3.8	
12	12	29	14	3.0	106.7	30.2	2.1	.0	74.2	8.2	48.4	1.2	27.9	-24.6	23.7	6.1	4.2	
13	12	29	15	2.5	87.6	24.8	10.6	.0	67.4	4.7	49.5	1.0	29.2	-25.1	24.3	6.0	4.9	
14	12	29	16	1.2	35.4	11.5	11.2	.0	42.3	-1.9	50.7	.3	30.0	-26.7	24.1	5.2	6.0	
15	12	29	17	.1	.0	1.4	4.1	.0	-4.3	-10.1	52.4	.4	30.0	-29.6	22.8	4.2	7.1	
16	12	29	18	.0	.0	.0	11.4	.0	-14.6	-5.9	53.9	.6	29.7	-31.8	22.1	4.2	7.6	
17	12	29	19	.0	.0	.0	2.8	.0	-15.6	-6.6	53.3	.5	29.4	-32.1	21.3	4.0	8.1	
18	12	29	20	.0	.0	.0	2.1	.0	-17.3	-5.5	52.3	.5	29.0	-31.7	20.6	4.1	8.5	
19	12	29	21	.0	.0	.0	2.1	.0	-19.2	-4.7	51.7	.5	28.7	-31.8	20.0	4.1	8.7	
20	12	29	22	.0	.0	.0	3.7	.0	-19.1	-4.5	52.6	.5	28.3	-33.2	19.4	4.2	8.9	
21	12	29	23	.0	.0	.0	2.1	.0	-19.4	-4.4	52.8	.5	27.9	-34.0	18.9	4.3	9.1	
22	12	30	0	.0	.0	.0	2.1	.0	-19.8	-4.1	52.9	.5	27.6	-34.6	18.4	4.3	9.2	
DAY	12	29	22	17.2	589.3	171.7	78.9	81.8			1133.6		26.7	-30.8	20.7	3.3	6.0	SUM-AVG

THERMAL PERFORMANCE
OF THE SHERIDAN SOLAR HOUSE

by

Charless W. Fowlkes

FOWLKES ENGINEERING
31 Gardner Park Drive
Bozeman, MT 59715

for

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
RENEWABLE ALTERNATIVE ENERGY SOURCES PROGRAM

John Orndorff, Bureau Chief

NOTICE

This report was prepared as an account of work sponsored by the Energy Division of the Montana Department of Natural Resources and Conservation through the Alternative Renewable Energy Sources Program. Neither the State of Montana, nor the Department, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

ABSTRACT

This project is an active-liquid solar system retrofit belonging to Dr. Richard Sheridan, Missoula, Montana. The free-standing collectors are located in a meadow about 200 feet from the house. The collectors deliver heat to water-filled heat storage tanks. A second liquid loop carries stored heat to an exchanger in the air duct which in turn delivers heat to the house.

The solar system does not deliver solar heat in mid-winter due, in part, to shading of the collector array. During the spring the collectors delivered 20% of the available solar insolation to the heat storage but only 3.6% to the house. The heat lost from the storage system did not go into the house. There appeared to be design and control problems in the storage-to-house heat exchange loop. The solar system supplied 7% of the heat load of the house during the monitoring period. It is estimated that system changes could increase the solar fraction to 25% on an annual basis.

The solar domestic hot water system was also monitored. It was a much better performer that the solar heating system. The DHW solar system delivered an average of 28% of the solar insolation to the preheat tank. This amounts to an average of 15 mega joules (16,000 Btu) each day.

NOTE ON UNITS

The data is presented in metric units. These units are in accord with the recommendations of the International Solar Energy Society as well as most current technical journals. The overall summaries and numbers in the test have been given in dual units. The heat load calculations are presented in conventional units.

Most readers are familiar with the Celsius or Centigrade temperature scale and are also familiar with energy units of kilowatt hours. The only other metric unit which occurs frequently in this report is the Joule (J), the metric unit of energy which replaces the Btu (a Btu is equal to 1,055 Joules). The mega joule (MJ) is equal to 10^6J (100,000 Btu/hr = 105 MJ/hr).

Other abbreviations used in this report include: m = meters; m^2 = square meters; l = liters; h = hours; gph = gallons per hour; and MBtu = millions of Btu's.

TABLE OF CONTENTS

1.0 Introduction 1
2.0 Acknowledgment 1
3.0 Description of Solar System 1
3.1 Monitoring Instrumentation 2
4.0 Data Base and Accuracy 3
5.0 Monitoring Data and Results
5.1 Site Survey 3
5.2 House Heat Load 4
5.3 Flow 4
5.4 Collector Efficiency 4
5.5 Heat Exchanger Effectiveness 5
5.6 Hourly Performance Summary 5
6.0 Overall Performance Summary 7
7.0 Comments and Conclusions 8
8.0 Predictions of Annual Performance 8
9.0 Graphical Presentation of Results 10

TABLES

Table 1 - Heat Load of Sheridan House 11
Table 2 - Summary of Manual Flow Meter Readings 12
Table 3 - Heat Exchanger Exit Temperature Differences 13
Table 4 - Hourly Performance Summary 14
Table 5 - Daily Summary 15
Table 6 - Daily Summary 16
Table 7 - Daily Summary 17
Table 8 - Solar Heating Summary for 78 Days, 3/20 to 6/18 18
Table 9 - Solar Hot Water Summary for 78 Data Days 19
Table 10 - Predicted Solar Radiation at Sheridan Site, kWh/m^2-day 19
Table 11 - Projected Average Daily Performance 20

FIGURES

Figure 1 - Schematic of Sheridan Solar Heating System Showing Instrumentation 21

Figure 2 - Sketch of Sheridan Residence Showing Window Areas 22

Figure 3 - Photographs of Main Collector Array 23

Figure 4 - Collector Panels 24

Figure 5 - Heat Storage System and Controls, Located in Basement 25

Figure 6 - Shading Diagram Showing Exposure of Collector Field to the Sun During the Winter 26

Figure 7 - Collector Efficiency Curves 27

Figure 8 - Computer Program of Heat Flow Equations Used for Performance Summary 28

Figure 9 - Table Headings for Performance Summary 29

Figure 10 - Sheridan Collector Performance Curve 30

Figure 11 - Graph of 5 Days Data in April 31

Figure 12 - Graph of 5 Days Data in May 32

Appendix I - Hourly Performance Data For Sheridan Solar System

1.0 INTRODUCTION

This project is in the residence of Dr. Richard Sheridan and is located on the north-facing slope of Pattee Canyon near Missoula. Dr. Sheridan, in addition to being a Professor at the University of Montana, is an active environmentalist and solar advocate. He is also an energetic and skilled craftsman and has designed and built his own house as well as the solar heating system monitored in this report.

The house was sited and built over 10 years ago. Solar orientation and energy conservation were not among the primary design considerations at that time. When Dr. Sheridan decided to retrofit solar collectors to his house, he located the collectors in a meadow about 200 feet from the house in order to gain exposure to the sun.

2.0 ACKNOWLEDGMENT

The cooperation and advice of Dr. Sheridan was crucial to the success of this monitoring project. He kept records of the readings of the manual flow meters which were necessary to characterize the average flow rates of the pumps. He contributed several suggestions concerning the behavior of the system and helped with the practical problems of installing the probes and routing the extension wires. The data tapes were changed by Dr. Sheridan and he alerted us when there were problems. We gratefully acknowledge his contributions and enthusiastic support of this monitoring project.

3.0 DESCRIPTION OF SOLAR SYSTEM

A schematic of the solar system is shown in Figure 1 and a house plan is shown in Figure 2. The main collector array consists of 24 liquid-cooled panels totalling 37.9 m^2 (408 ft^2) in area and tilted at 45° and facing south, Figure 3. The collectors are double glazed and have an insulated wood frame. The absorber plate is painted flat black and is attached to copper tubes about 10 cm (4 in) on center. Heat transfer putty was used between the tubes and the absorber plate. This material has been unsatisfactory as it runs out of the joint at higher temperatures as shown in Figure 4(a). The absorber plates are manifolded and the fluid carried to the storage tanks in the house through pipes enclosed in foam insulation, Figure 3(d).

The collector fluid is a 50% ethylene glycol-water mixture having a density of 1.07 kg/l and a specific heat of 3.18 kJ/kg°C. The collector pump is powered by a 3/4-hp electric motor and produces a flow of 2089 lph (552

gph). The collector fluid passes through finned tubes immersed in three fiberglass heat storage tanks each filled with 5,677 l (500 gal) of water. One tank is divided so that storage mass can be adjusted to four levels by setting appropriate values, Figure 1. The heat storage tanks are located in a basement garage and are individually insulated with R-11 fiberglass. Figure 5 shows the tanks and the circulating pumps.

Heat removal from storage is shown in the schematic diagram in Figure 1. Fluid is circulated by a 1/12-hp pump which delivers a flow of 587 lph (155 gph). The fluid passes through finned tubes in the heat storage tanks and then through finned tubes located in an air duct supplying the house, Figure 5(a). An auxiliary hot-air, oil furnace is also connected to this duct. Additional auxiliary heat is supplied by a wood-burning stove, Figure 1.

The domestic hot water solar pre-heat system is also shown in Figure 1. The collectors, Figure 4(b), are similar in construction to the main collector array and have an area of 4.7 m^2 (51 ft^2). A 50% ethylene glycol-water mixture is circulated by a pump delivering an average flow of 250 lph (66 gph). This flow is adjusted manually by the owner to control the collector outlet temperature. The collector fluid passes through an exchanger in a pre-heat tank having a capacity of 405 l (105 gal). Well water enters the pre-heat tank and then goes through a conventional electric water heater.

3.1 Monitoring Instrumentation

The transducer arrangement is shown in the system schematic diagram in Figure 1. This solar system has many components and heat transfer loops making characterization and instrumentation a formidable problem. The owner was interested in the performance of the solar domestic hot water system and believed that it would prove to be more efficient than his solar space heating system. Because of these considerations, the available instrumentation resources were focused on the solar components of the system; the oil furnace and wood stove heating systems received secondary attention.

The solar collector loop was instrumented with a continuous reading flow meter, a status relay on the pump motor and three temperature transducers. Two of these transducers measured inlet and outlet collector temperatures at the storage tank to determine solar heat delivered to the storage. An extra probe measured the collector outlet temperature at the point where the total collector flow left the array and started toward the house, location D in

Figure 3. This allowed an estimate of the heat loss due to the remote location of the collector array. Solar insolation was measured at the center of the array and in the plane of the collectors.

The average temperature of the thermal storage was sampled with three probes attached to the surfaces of the three heat storage tanks. The probes were covered with heat transfer putty and insulated. Net heat changes in the storage system are reflected by the change of these temperatures with time.

The heat extraction loop was instrumented with a manual-reading flow meter, a status relay on the pump motor and temperature probes on the inlet and outlet pipes. The DHW collector loop was similarly instrumented. A probe on the DHW storage tank reflected energy changes in the tank. Electric power is monitored continuously as well as house temperature and ambient temperature. A probe in the furnace outlet duct allowed for an approximate calculation of auxiliary furnace heat output.

4.0 DATA BASE AND ACCURACY

The relative accuracy of the temperature measurements was 0.2°C and the accuracy of temperature changes was better than 0.1°C. The flow meters are accurate to within 3%. The electric power measurements are calibrated against the watt meter and are correct within 3%. The solar insolation is accurate to within 5% on the basis of average daily total insolation. The accuracy of the calculated heat flows changes depending on the size of the temperature difference. On the average the error is believed to be no more than 15%.

The data acquisition system was installed March 19, 1979 and removed June 19, 1979. A total of 1919 hours of data were recorded for 18 transducer channels of 34,542 hourly average data values. Each hourly average consisted of about 660 individual readings; hence, the data base contains about 23,000,000 channel readings. The total missing data was 12% and was primarily due to a data tape that was not replaced when it ran out.

5.0 MONITORING DATA AND RESULTS

5.1 Site Survey

A shading profile taken in the center of the collector array is shown in Figure 5. The arcs show the path of the sun during winter between the fall and spring equinox for various times of day. The composite photograph

shows the view of the sky looking south, seen by the collector array. The shading profile indicates that there is a high percentage of shading during the months of November, December and January. The implications of this shading diagram are substantiated by Dr. Sheridan's reports that the solar system puts out little or no heat during this season.

5.2 House Heat Load

The calculated heat load factor of the house is shown in Table 1. Dominating features affecting the heat load include a large cathedral window on the north end of the building and a large roof area inherent in the A-frame design, which is insulated to R-10. Dr. Sheridan reports that he reduces the heat requirements of the house by (a) closing off bedrooms, (b) reducing the thermostat when the house is unoccupied and at night, and (c) keeping the house temperatures around 16°C (60°F). The data demonstrates some of these patterns.

5.3 Flow

The manual flow meter readings taken daily by Dr. Sheridan are reproduced in Table 2. The net daily flows were divided by the daily on-time of the respective pumps to yield a daily average flow rate for each system. A large number of these readings were averaged to produce flow rate values which were subsequently used to perform the hourly heat balances. Checks on the heat balance of the storage system showed these values to be reliable. The flow meters have an accuracy of better than 3% and their calibration was checked after removal from the test site. The calibration facility at the Bozeman City Water Department was used for these determinations.

5.4 Collector Efficiency

Efficiency curves for the Sheridan collectors are shown in Figure 6 along with a HUD reference curve for this general type of collector. The "output" of the test collector was defined as heat delivered to the storage system. The collector is thus penalized for heat losses in the extensive piping and manifold system between the collectors and the storage tanks. This loss appears to be around 10% of the output. The temperature rise of the liquid flows through the collector was typically 5° to 10°C (9° to 18°F). The temperature drop between the collector array outlet and the storage tank inlet was around 0.5°C (1°F). This indicates about a 5% loss in that section

of piping. The losses in the manifold piping within the collector field appear to be another 5%.

5.5 Heat Exchanger Effectiveness

Table 3 shows a modified version of the final, hourly summary program for two typical days. The columns of interest in this table are noted (1), (2) and (3) and give information on the effectiveness of the three primary heat exchangers. The value of the $\triangle T$ (temperature differences) leaving each of the heat exchangers. If the heat exchangers were 100% effective, the fluid leaving the exchanger would be equal to the heat exchanger temperature and these $\triangle T$ values would be "0".

The exchangers (1) and (2), "into" and "out of" the heat storage tank are finned tube liquid exchangers. For the collector exchanger (1), the temperature change through the exchanger (not shown) is of the same order as the $\triangle T$ leaving the exchanger. For exchanger (2), the temperature change through the exchanger (not shown) is around .25 to .5 of the $\triangle T$ leaving the exchanger. The other end of exchanger (2) is a finned tube in the house air duct (3). The $\triangle T$ between the exit fluid and the air is around $20^{o}C$ ($36^{o}F$).

These data indicate that the heat exchange loop from the storage to the house has a low effectiveness at both ends and is not doing an efficient job of moving the heat from the storage to the house. The collector-to-storage heat exchanger does a much more efficient job.

5.6 Hourly Performance Summary

The fundamental unit of the performance data is the hourly summary. This summary includes all the individual heat flows and allows determination of their contributions to the overall system. Figure 8 lists the portion of the computer program used to process the hourly data to compute heat quantities.

Figure 9 explains the quantities tabulated in the overall performance summary. In general, this summary traces the hourly average flow of energy from solar radiation, to collectors, to storage and to the house (or the DHW tank). Auxiliary heat inputs due to electrical dissipation and the furnace are tabulated. The hourly house heat loss is based on the heat load factor, Table 1, and the measured difference in temperature between the inside and outside of the house. Temperatures at important points in the system are also tabulated.

The hourly performance for 35 days is given in the tables in Appendix I. As an example of the use of this information, look at Table 4 for the day of April 24. The sun came up between 7 and 8 AM and set after 8 PM; see "SOLAR INSO" column. The collector pump turned on shortly before 11 AM and delivered heat to storage until 4 PM (18 hours); see "COLL OUTPT" column. The storage output column, "STORE OUTPT", shows a loss of 2.1 MJ/hr during the early morning hours. The storage begins delivering heat to the house between 10 and 11 AM and begins receiving significant heat from the collectors between 11 AM and noon.

It should be noted that the hourly "COLL OUTPUT" and "STORE HOUSE" quantities are much more accurate than the "STORE OUTPT" quantities. The storage output is calculated from the temperatures measured at only three points in the storage system. The temperature differences are also small and one-half hour out of phase. The combination of these features causes the hourly values to lag and to fluctuate. The average values taken over one or two days, however, balance as they should: i.e., Input = Output + Loss. The use of the "STORE OUTPT" column is to give a rough check on the "COLL OUTPT" AND "STORE HOUSE" quantities and to determine the average heat loss factor for the heat storage system.

The "DHWC OUTPT" is the heat delivered by the domestic hot water collectors to the heat storage tank. "DELTA DHW" is again calculated on the temperature change of one probe on the DHW tank and shows the lag and hourly fluctuation previously discussed.

The "DELTA DHW" column shows that the heat loss was less than 0.05 MJ/hr during the early morning hours. Between 7 and 9 AM some heat was removed from the tank probably due to normal household uses. Between 10 and 11 AM the DHW collectors turned on and began delivering heat to the tank. Small amounts of heat were withdrawn during the evening. (Also note the increased hourly heat loss due to the higher tank temperature.) Between 10 PM and midnight (23 and 0 hrs.) it appears that there were significant withdrawals from the tank, perhaps due to baths or washing dishes or clothes. Note that the electric power between 10 and 11 PM (23 hrs.) increased markedly, probably due to the auxiliary DHW heater. The "FURNC DUCT" column shows that the furnace was used for about 3 hours in the morning when the Sheridans got up.

The hourly electric power use (divide MJ by 3.6 to get kWh) is typical in that it shows the morning and evening peaks. The steady daytime use of about 2.5 MJ (.7 kW) is mostly due to the solar circulating pumps.

The bottom line of the summary shows the daily sum of all energy items and the average of the temperature items. The total heat inputs to the house on this day consisted of 112 MJ from solar storage, 52 MJ electric power and 168 MJ from the auxiliary furnace. This total of 332 MJ compares tolerably well with the calculated heat loss of 416 MJ. It is possible that the wood stove was being used in the evening as the house temperature peaks at 21.2°C (70°F) at 9 PM.

There is a wealth of information concerning the dynamic behavior of the solar system contained in the hourly and daily summaries in Appendix I. In order to summarize this information all the data in Appendix I have been condensed into daily summaries covering the entire monitoring period. These data are given in Tables 5, 6 and 7. The headings and units are the same as discussed previously.

6.0 OVERALL PERFORMANCE SUMMARY

This data has been further summarized to produce the results in Tables 8 and 9. Table 8 summarizes the data for the solar heating system for 78 data days between March 20 and June 18, 1979. This data shows that the collectors delivered 20% of the available radiation to the storage tanks. Of this stored solar heat, 18% was delivered to the house, the remainder being lost to the garage.

The second part of Table 8 compares the overall heat load of the house to the relative contributions of the solar system and the auxiliary system. This table shows that the solar heating system contributed 7% and the auxiliary systems (furnace and wood) contributed 85%. The remaining heat was electrical dissipation due to appliances and lights, estimated as 0.6 of the total electrical consumption.

Table 9 summarizes the performance of the domestic hot water solar system. Solar insolation was not measured at the DHW collector panel. Because of its shaded location, it was assumed to be exposed to 0.75 of the solar radiation measured in the main collector field. Based on this estimate, the collector delivered 28% of the incident radiation to the tank. If the average heat loss of the tank is considered, the useful heat output amounts to 24% of the incident radiation.

7.0 COMMENTS AND CONCLUSIONS

This solar heating system has three characteristics which reduce its performance:

(1) The collectors are shaded in mid-winter.

(2) There are heat losses of about 10% in the piping between the collector array and the house.

(3) Only 18% of the heat that does get into the storage tanks is delivered to the house.

Items (1) and (2) could not be avoided due to the sitting of the house. Item (3) appears to have three main causes:

(a) Heat lost from the storage tanks does not enter the house envelope and is, thus, truly lost.

(b) The heat exchangers between the storage tanks and the house have limited ability to transfer heat to the house. Data in Table 3 as well as the hourly performance suggests that these exchangers should be of higher efficiency.

(c) The storage-to-house exchangers do not operate on a large percentage of the days even though the storage is charged to temperatures of 40-50°C (104-122°F); see Tables 5, 6 and 7.

If all the heat collected during the monitoring period could have been delivered to the house, the solar fraction would have been 27% instead of 7%.

The domestic hot water system has a better overall performance in terms of useful heat delivered. Since the storage tank is located inside the house, losses from this tank contribute useful heat to the house.

8.0 PREDICTIONS OF ANNUAL PERFORMANCE

In this section the performance during the monitoring period is projected to create an estimate of the annual performance. The starting point of this analysis is the environmental data concerning the solar radiation available and the ambient temperatures or degree days.

The solar radiation measured at the Hellgate High School in Missoula is compared with the radiation measured at the Sheridan site in Table 10. The Missoula data is taken from measurements made as part of the SIMM program sponsored by the Department of Natural Resources and Conservation. The measurements were taken on a 60° tilted surface. This data is mathematically adjusted to correspond to a 45° tilted surface, the plane of the monitoring devices on the Sheridan collectors. The predicted data and the data measured on-site show satisfactory agreement.

Figure 10 is a graph of the performance of the Sheridan solar collectors during the monitoring period. The total insolation striking the collector field is plotted against the heat delivered by the collectors to the storage system. A single curve has been drawn through these points. This curve is assumed to characterize the daily output of the collectors given a solar input. The scatter of the data points shows that the straight line is only an approximation to the data.

Table 11 compiles the projected annual performance. Long-term average degree day/month data for Missoula is listed in the first column. This data is based on 18.3°C (65°F). The second column is the degree day data adjusted for a house temperature of 16°C (60°F) to better reflect the real average temperature of the Sheridan house.

The next column, INSOL @ 60°, is the average daily solar radiation recorded in Missoula on a 60° tilt during the time period from July 1978 to June 1979. The factor in the next column adjusts this data to the 45° tilt of the Sheridan collectors. This value multiplied by the area of Sheridan's collector array and converted to mega joules is listed in the next column, TOTAL INSO. This is the total radiation intercepted by the collectors assuming no shading.

This total radiation is then converted to the collected radiation using Figure 10 and is listed as SOLAR COLLECT in the next column. The next column is the fraction of the collected energy that is actually delivered to the house, based on the average performance during the monitoring period. The heat load is then calculated for the average day based on the heat load factor in Table 1 and the adjusted degree days. If the solar collected or delivered is greater than the heat load, the excess heat is not usable. In these cases the heat load is shown in parentheses in the solar column and represents the maximum usable heat delivered. The solar fraction on these days is 1.00 or 100% and can be no greater.

This analysis predicts that the annual solar heat delivered by the system will be 5,760 MJ (6.2×10^6 Btu) or 6% of the annual heat load. The analysis shows that insignificant amounts of heat are delivered during November, December and January. These estimates are in general agreement with Dr. Sheridan's reports on the actual output of the system during these months.

If the solar heat that is currently being delivered to the storage system, SOLAR DELVD, could be effectively used in the house, the solar fraction would be much larger. This assumption is represented in Table 11 for

comparison. These results predict that 25% of the heating load would be met by the solar system in this hypothetical situation. This could be practically accomplished by locating the heat storage inside the house instead of the garage and increasing the effectiveness of delivering stored solar heat to the house.

9.0 GRAPHICAL PRESENTATION OF RESULTS

A graphical presentation of the hourly data for two-five day periods is presented in Figures 11 and 12. The figures contain data for solar insolation and four temperatures. The general pattern shows the daily increase in storage tank temperatures due to the addition of solar heat. The decrease in storage temperature reflects heat loss or an intentional withdrawal of heat. The slopes of the storage temperature at night show that the DHW tank loss rate is less than the main storage loss rate. Note the small temperature drops during the mornings of 4/28 and 4/29 in Figure 11. These correspond to heat withdrawals by the house pump. The columns STORE HOUSE in Tables 4 and 5 in Appendix I show the amount of heat taken from storage (as measured in the storage-to-house heat exchanger).

Note that the DHW tank temperature shows large energy withdrawals most mornings and evenings. This is a typical household use pattern. The graphs illustrate that the solar DHW heat is being "used" while most of the solar heating energy is being dissipated gradually into the garage. The data tables (Appendix I) give more quantitative results for the energy flows. Graphs such as those shown in Figures 11 and 12 are useful for de-bugging and checking the data. They are also fun to look at.

TABLE 1

HEAT LOAD OF SHERIDAN HOUSE

	R	U (Btu/hr ft^2 $^\circ$F)	AREA (sq. ft.)	U X A
Roof	10	.10	1757	176
Walls	15.2	.065	1224	79.5
*Floor	30	.033	1288	43
Windows	1.5	.65	324	210.6
**Infiltration: 18,676 ft^3 X $\frac{1}{2}$ X .018				168
			Total Heat Load	677 Btu/hr $^\circ$F or 1.28 MJ/hr $^\circ$C

*Effective R due to insulated basement

**4$\frac{1}{2}$ air change/hr

— TABLE 2 —

SUMMARY OF MANUAL FLOW METER READINGS (GALLONS)

(1) STORAGE TO HOUSE

(2) SOLAR TO DHW

DATE		METER(1)	METER(2)	FLOW(1)	FLOW(2)
MAR	22	115.00	54.00	700.00	310.00
MAR	23	189.00	77.00	740.00	230.00
MAR	24	299.00	105.00	1100.00	280.00
MAR	25	399.00	136.00	1000.00	310.00
MAR	26	460.00	158.00	610.00	220.00
MAR	27	460.00	158.00	.00	.00
MAR	28	460.00	158.00	.00	.00
MAR	29	460.00	158.00	.00	.00
MAR	30	460.00	186.00	.00	280.00
MAR	31	460.00	192.00	.00	60.00
APR	1	460.00	194.00	.00	20.00
APR	2	460.00	199.00	.00	50.00
APR	3	460.00	212.00	.00	130.00
APR	4	460.00	218.00	.00	60.00
APR	5	460.00	223.00	.00	50.00
APR	6	460.00	251.00	.00	280.00
APR	7	460.00	263.00	.00	120.00
APR	8	460.00	283.00	.00	200.00
APR	9	460.00	304.00	.00	210.00
APR	10	460.00	304.00	.00	.00
APR	11	460.00	304.00	.00	.00
APR	12	521.00	339.00	610.00	350.00
APR	13	560.00	368.00	390.00	290.00
APR	14	560.00	386.00	.00	180.00
APR	15	560.00	409.00	.00	230.00
APR	16	560.00	426.00	.00	170.00
APR	17	560.00	460.00	.00	340.00
APR	18	560.00	485.00	.00	250.00
APR	19	560.00	496.00	.00	110.00
APR	20	560.00	516.00	.00	200.00
APR	21	560.00	543.00	.00	270.00
APR	22	600.00	581.00	400.00	380.00
APR	23	707.00	597.00	1070.00	160.00
APR	24	712.00	601.00	50.00	40.00
APR	25	892.00	633.00	1800.00	320.00
APR	26	892.00	657.00	.00	240.00
APR	27	906.00	693.00	140.00	360.00
APR	28	925.00	731.00	190.00	380.00
APR	29	943.00	766.00	180.00	350.00
APR	30	1030.00	788.00	870.00	220.00
MAY	1	1060.00	814.00	300.00	260.00
MAY	2	1060.00	840.00	.00	260.00
MAY	3	1060.00	877.00	.00	370.00
MAY	4	1060.00	911.00	.00	340.00
MAY	5	1100.00	911.00	400.00	.00
MAY	6	1112.00	912.00	120.00	10.00
MAY	7	1135.00	939.00	230.00	270.00
MAY	8	1176.00	975.00	410.00	360.00
MAY	9	1246.00	1008.00	700.00	330.00
MAY	10	1275.00	1035.00	290.00	270.00
MAY	11	1392.00	1058.00	1170.00	230.00
MAY	12	1404.00	1099.00	120.00	410.00
MAY	13	1419.00	1133.00	150.00	340.00
MAY	14	1419.00	1170.00	.00	370.00
MAY	15	1461.00	1206.00	420.00	360.00
MAY	16	1461.00	1243.00	.00	370.00
MAY	17	1462.00	1255.00	10.00	120.00
MAY	18	1462.00	1290.00	.00	350.00
MAY	19	1462.00	1323.00	.00	330.00
MAY	20	1462.00	1366.00	.00	430.00
MAY	21	1487.00	1409.00	250.00	430.00
MAY	22	1511.00	1456.00	240.00	470.00
MAY	23	1511.00	1502.00	.00	460.00
MAY	24	1511.00	1549.00	.00	470.00
MAY	25	1511.00	1563.00	.00	140.00
MAY	26	1511.00	1614.00	.00	510.00
MAY	27	1511.00	1661.00	.00	470.00
MAY	28	1557.00	1703.00	460.00	420.00
MAY	30	1612.00	1734.00	550.00	310.00
MAY	31	1668.00	1775.00	560.00	410.00
JUN	1	1735.00	1818.00	670.00	430.00
JUN	2	1748.00	1872.00	130.00	540.00
JUN	3	1776.00	1909.00	280.00	370.00
JUN	4	1799.00	1960.00	230.00	510.00
JUN	5	1801.00	2013.00	20.00	530.00
JUN	6	1801.00	2064.00	.00	510.00
JUN	7	1843.00	2079.00	420.00	150.00
JUN	8	1923.00	2101.00	800.00	220.00
JUN	9	1991.00	2147.00	680.00	460.00
JUN	10	2012.00	2194.00	210.00	470.00
JUN	11	2012.00	2250.00	.00	560.00
JUN	12	2012.00	2305.00	.00	550.00
JUN	13	2012.00	2359.00	.00	540.00
JUN	14	2012.00	2412.00	.00	530.00
JUN	15	2012.00	2463.00	.00	510.00
JUN	16	2012.00	2516.00	.00	530.00
JUN	17	2012.00	2540.00	.00	240.00
JUN	18	2012.00	2579.00	.00	390.00
JUN	19	2012.00	2579.00	.00	.00
JUN	20	2113.00	2579.00	1010.00	.00

TABLE 3

HEAT EXCHANGER EXIT TEMPERATURE DIFFERENCES

DAILY PERFORMANCE SUMMARY FOR SHERIDAN HOUSE (ID='11')

UNITS: ENERGY-MJ,TEMPERATURE-DEG C

RECH	MO	DAY	HR	SOLAR INSO	COLL OUTPT	STORE OUTPT	STORE HOUSE	DHWC OUTPT	DELTA DHW	ELECT POWER	(1) COLEX DELT T	(2) STOEX DEL T	STORE TEMP	AMBNT TEMP	HOUSE TEMP	(3) HOSEX DEL T	DEGRE HOUR
550	5	22	5	.0	.0	-8.8	.0	.0	-.2	8.9	.0	.0	66.6	8.1	19.9	.0	11.8
551	5	22	6	.0	.0	-8.3	.0	.0	-.7	11.5	.0	.0	66.3	7.3	19.5	.0	12.2
552	5	22	7	1.3	.0	-8.6	4.6	.0	-7.8	33.8		7.4	65.9	7.8	19.7	29.9	11.9
553	5	22	8	2.6	.0	-18.6	11.9	.0	-5.1	31.4	(2)	6.5	65.2	9.1	19.8	31.1	
554	5	22	9	15.9	.0	-24.3	12.5	.0	-.4	13.3	.0	7.1	64.1	10.6	19.7	30.3	(3)
555	5	22	10	43.7	.0	-17.4	.9	.0	-.2	6.7	.0	2.7	63.4	12.5	19.6	32.4	
556	5	22	11	94.0	-2.4	-7.8	.0	1.5	.1	4.9	-16.1	.0	63.1	15.9	19.5	.0	3.6
557	5	22	12	116.5	31.1	5.7	.0	3.6	3.3	14.1	6.0	.0	63.3	18.3	20.0	.0	1.6
558	5	22	13	127.1	45.2	50.0	.0	4.7	7.3	12.7	8.8	.0	65.4	20.3	20.5	.0	.3
559	5	22	14	131.0	48.8	61.8	.0	5.0	7.5		9.3	.0	68.0	22.0	21.2	.0	-.8
560	5	22	15	125.7	43.4	60.4	.0	4.5	7.1	(1)	8.3	.0	70.6	22.9	22.0	.0	-.9
561	5	22	16	109.8	32.5	46.1	.0	3.6	6.2		6.1	.0	72.5	24.0	22.7	.0	-1.2
562	5	22	17	83.4	17.4						3.1	.0	73.5	24.4	23.5	.0	-1.0
563	5	22	18	22.5	1.4						-1.8	.0	73.6	24.9	24.1	.0	-.8
564	5	22	19	4.0	.0						.0	.0	73.2	24.4	24.8	.0	.4
565	5	22	20	2.6	.0	(1) Collector exchanger ΔT					.0	.0	72.8	22.3	24.9	.0	2.5
566	5	22	21	.0	.0	ΔT = T(coll.ret.)-T(storage)					.0	.0	72.4	17.8	24.4	.0	6.6
331	5	13	1	.0	.0						.0	.0	51.2	4.8	16.3	.0	11.5
332	5	13	2	.0	.0	(2) Storage exchanger ΔT					.0	.0	50.9	4.3	15.8	.0	11.5
333	5	13	3	.0	.0						.0	.0	50.7	3.9	15.4	.0	11.5
334	5	13	4	.0	.0	ΔT = T(storage)-T(outlet)					.0	.0	50.5	3.1	15.0	.0	11.9
335	5	13	5	.0	.0						.0	.0	50.3	2.4	14.5	.0	12.0
336	5	13	6	.0	.0						.0	.0	50.0	2.0	14.1	.0	12.1
337	5	13	7	4.0	.0	(3) House duct exchanger ΔT					.0	.0	49.8	3.3	14.0	.0	10.7
338	5	13	8	7.9	.0	ΔT = T(return)-T(house)					.0	6.4		5.0	14.2	23.0	9.2
339	5	13	9	22.5	.0						.0	6.0	(2)	7.2	15.4	22.9	8.2
340	5	13	10	42.4	.0						.0	5.2		8.6	18.0	20.4	
341	5	13	11	60.9	-.1						-6.8	2.1	48.1	11.3	18.7	22.0	(3)
342	5	13	12	39.7	3.5						1.8	4.2	48.0	13.3	18.8	18.2	
343	5	13	13	58.2	13.7						4.0	.0	48.0	14.7	18.0	.0	3.3
344	5	13	14	64.8	20.7	20.2	.0	2.3	3.7		4.6	.0	48.8	15.4	18.4	.0	3.0
345	5	13	15	37.1	5.0	17.8	.0	1.1	3.2	(1)	3.2	.0	49.6	15.8	18.5	.0	2.7
346	5	13	16	18.5	.0	-1.0	.0	.0	1.1		.0	.0	49.5	15.4	18.6	.0	3.2
347	5	13	17	43.7	2.0	-3.3	.0	1.1	.6	20.4	-1.0	.0	49.4	17.2	19.1	.0	1.9

SIMM Data Reduced - 1977

		# Days	Aver. Day*	Aver. Clear Day*	Aver. Day / Aver. CD (%)	# Clear Days
Miles	Jan	10	3.404	5.618	61	1
	Feb	28	4.037	6.022	67	2
	Mar	31	4.283	6.441	66	2
	Apr	30	5.174	6.106	85	6
	May	31	4.248	est	(84)	0
	Jun					
	Jul					
	Aug					
Polsn	Jan	8	1.919	est	(31)	0
	Feb	28	2.395	6.367	38	1
	Mar	31	3.100	est	(44)	0
	Apr	30	5.078	6.571	77	5
	May	31	4.071	est	(68)	0
	Jun	30	4.634	5.712	81	2
	Jul	31	4.510	5.803	78	3
	Aug					

* kW-hrs/m^2/day

NOTE: kW/m^2 x 316 = BTU/hr-ft^2

		# Days	Aver. Day*	Aver. Clear Day*	Aver. Day / Aver. CD (%)	# Clear Days
Misla	Jan	12	2.608	est	(46)	0
	Feb	28	3.008	5.851	51	1
	Mar	31	2.739	6.426	43	1
	Apr	30	4.770	6.331	75	4
	May	31	3.511	est	(69)	0
	Jun	28	4.405	5.544	79	3
	Jul	30	3.949	5.413	73	4
	Aug	31	4.446	6.128	73	7
WYell	Jan	9	4.748	6.117	78	2
	Feb	28	4.728	6.527	72	3
	Mar	31	3.728	6.564	57	2
	Apr	28	4.518	6.158	73	2
	May	31	3.318	est	(52)	0
	Jun	30	4.056	4.745	85	3
	Jul	16	4.319	est	(74)	0
	Aug					

* kW-hrs/m^2/day

NOTE: kW/m^2 x 316 = BTU/hr-ft^2

TABLE 4

DAILY PERFORMANCE SUMMARY FOR SHERIDAN HOUSE (ID='II')

UNITS: ENERGY-MJ,TEMPERATURE-DEG C

RECH	MO	DAY	HR	SOLAR INSO	COLL OUTPT	STORE OUTPT	STORE HOUSE	DHWC OUTPT	DELTA DHW	ELECT POWER	FURNC DUCT	HOUSE LOAD	STORE TEMP	AMBNT TEMP	HOUSE TEMP	STORE LOSS	DEGRE HOUR	
53	4	24	1	.0	.0	-2.1	.0	.0	-.3	1.0	.0	18.8	43.6	1.9	16.6	.1	14.7	
54	4	24	2	.0	.0	-2.1	.0	.0	-.0	.3	.0	18.9	43.5	1.3	16.0	.1	14.8	
55	4	24	3	.0	.0	-2.1	.0	.0	.0	.6	.0	17.8	43.4	1.6	15.5	.1	13.9	
56	4	24	4	.0	.0	-2.1	.0	.0	.0	.3	.0	17.4	43.4	1.5	15.1	.1	13.6	
57	4	24	5	.0	.0	-2.1	.0	.0	.0	.6	.0	16.7	43.3	1.5	14.6	.1	13.1	
58	4	24	6	.0	.0	-2.1	.0	.0	.0	.3	.0	16.3	43.2	1.5	14.2	.1	12.7	
59	4	24	7	.0	.0	-2.1	.0	.0	.0	.7	.0	16.1	43.1	1.2	13.8	.1	12.6	
60	4	24	8	1.3	.0	-2.4	.0	.0	-.7	4.4	72.8	21.3	43.0	1.6	18.2	.1	16.7	
61	4	24	9	9.3	.0	-2.1	.0	.0	-1.5	4.2	55.1	21.4	42.9	2.6	19.4	.1	16.8	
62	4	24	10	19.9	.0	-2.4	.5	.0	-.1	2.4	38.1	20.0	42.8	3.5	19.2	.1	15.7	
63	4	24	11	37.1	.5	-4.8	5.0	-.0	-.1	1.5	1.5	17.1	42.6	5.1	18.5	.1	13.4	
64	4	24	12	96.6	13.9	-9.8	6.3	3.3	1.2	2.1	.0	15.0	42.2	6.5	18.2	.3	11.7	
65	4	24	13	83.4	30.2	21.9	7.8	3.5	5.3	2.7	.0	14.1	43.1	7.6	18.6	-.7	11.0	
66	4	24	14	96.6	40.2	35.9	9.2	4.4	5.5	2.5	.0	12.7	44.6	9.0	18.9	-1.1	9.9	
67	4	24	15	83.4	25.5	31.4	9.5	3.0	4.8	2.3	.0	12.4	45.9	9.7	19.4	-1.0	9.7	
68	4	24	16	95.3	37.0	31.6	10.1	4.2	5.4	2.5	.0	11.8	47.3	10.7	19.9	-.9	9.2	
69	4	24	17	56.9	18.5	25.0	10.1	2.0	4.4	2.4	.0	12.0	48.3	11.1	20.5	-.7	9.3	
70	4	24	18	27.8	1.9	-2.1	9.8	.5	2.1	1.9	.0	12.8	48.2	10.6	20.6	.1	10.0	
71	4	24	19	13.2	.0	-16.4	9.4	.0	.2	1.2	.0	14.0	47.5	9.5	20.5	.5	10.9	
72	4	24	20	2.6	.0	-17.1	9.1	.0	-.5	6.0	.0	16.6	46.8	8.0	20.9	.5	12.9	
73	4	24	21	.0	.0	-16.7	8.8	.0	-.7	2.0	.0	18.1	46.1	7.0	21.2	.5	14.2	
74	4	24	22	.0	.0	-15.7	8.7	.0	-.7	1.8	.0	18.5	45.5	6.3	20.7	.5	14.5	
75	4	24	23	.0	.0	-15.2	7.5	.0	-3.9	4.7	.0	18.6	44.8	5.9	20.4	.4	14.5	
76	4	25	0	.0	.0	-8.6	.0	.0	-2.2	.8	.0	18.1	44.5	5.1	19.3	.2	14.1	
DAY	4	24	25	623.4	167.7	15.7	111.8	20.8	17.2	52.7	167.8	416.4	44.5	5.3	18.3	-.0	13.5	SUM-AVG

DAILY PERFORMANCE SUMMARY FOR SHERIDAN HOUSE (ID='I')

UNITS: ENERGY-MJ,TEMPERATURE-DEG C

CH	MO	DAY	HR	SOLAR INSO	COLL OUTPT	STORE OUTPT	STORE HOUSE	DHWC OUTPT	DELTA DHW	ELECT POWER	FURNC DUCT	HOUSE LOAD	STORE TEMP	AMBNT TEMP	HOUSE TEMP	STORE LOSS	DEGRE HOUR	
Y	3	20	11	324.2	92.9	22.8	44.9	15.3	4.5	26.2	.0	192.0	49.6	4.0	17.7	-.1	13.6	SUM-AVG
Y	3	21	24	821.9	249.0	109.9	62.9	23.7	14.6	43.2		410.0	50.5	2.9	16.3	-.1	13.9	SUM-AVG
Y	3	22	24	606.1	113.8	-45.0	36.8	15.0	-7.9	40.1		415.0	51.9	3.2	16.7	.0	14.1	SUM-AVG
Y	3	23	24	786.1	219.5	79.4	82.8	26.2	5.0	49.8		412.6	52.2	3.3	16.7	-.1	14.0	SUM-AVG
Y	3	24	24	825.8	227.0	-9.5	152.7	25.3	7.5	47.0		332.3	53.9	6.0	16.8	-.0	11.4	SUM-AVG
Y	3	25	24	537.3	82.8	-110.6	118.8	9.5	-14.7	42.5		423.4	51.4	3.4	17.1	.1	14.3	SUM-AVG
Y	3	26	24	168.1	.0	-88.2	.0	.0	-10.2	31.1		506.3	46.9	-.2	16.3	.1	17.1	SUM-AVG
Y	3	27	24	68.8	.0	-74.5	.0	.0	-6.8	34.4		555.2	43.5	-1.7	16.4	.1	18.8	SUM-AVG
Y	3	28	20	199.8	-.2	-48.3	.0	.5	-2.5	24.2		488.0	40.9	-3.1	15.9	.1	20.0	SUM-AVG
Y	3	31	13	176.0	1.6	-23.3	.0	1.0	-1.2	27.9	336.6	336.4	39.8	-.1	20.1	.1	21.8	SUM-AVG
Y	4	1	24	303.1	8.5	-42.3	.0	2.9	.3	30.3	328.6	559.7	38.1	-2.2	16.0	.1	19.1	SUM-AVG
Y	4	2	24	390.4	55.0	19.7	.0	7.2	3.9	38.8	548.1	518.3	37.4	-1.4	15.5	-.0	17.7	SUM-AVG
Y	4	3	24	300.4	21.4	-26.2	.0	4.0	-1.1	36.9	512.8	497.2	37.5	.3	16.5	.0	16.9	SUM-AVG
Y	4	4	24	226.3	18.1	-23.8	.0	3.3	-.3	42.8	470.7	448.9	36.5	2.5	17.1	.0	15.3	SUM-AVG
Y	4	5	24	559.8	173.0	190.8	.0	19.5	15.0	36.4	349.8	364.4	39.2	6.5	18.4	-.3	12.5	SUM-AVG
Y	4	6	24	267.3	23.6	-54.2	.0	3.6	-4.2	38.6	541.1	388.0	42.7	5.8	18.4	.1	13.1	SUM-AVG
Y	4	7	24	402.3	59.9	3.8	.0	9.0	-4.8	59.8	534.6	409.0	41.5	4.8	18.1	-.0	13.9	SUM-AVG
Y	4	8	24	416.9	82.2	32.6	.0	10.4	1.7	47.3	436.5	384.6	42.3	5.8	18.3	-.1	13.1	SUM-AVG
Y	4	9	23	70.1	-97.4	-62.8	23.7	.0	-5.9	36.9	645.6	463.0	40.0	2.0	17.7	-289.5	16.3	SUM-AVG
Y	4	10	23	101.9	.0	-51.6	.0	-10.1	-4.6	34.9	482.1	418.5	37.9	2.1	16.3	-2.7	14.9	SUM-AVG
Y	4	11	23	825.8	246.7	200.5	45.3	26.8	25.3	51.1	257.8	508.0	43.0	-.4	16.9	-.2	17.9	SUM-AVG
Y	4	12	24	520.1	95.1	-23.5	28.1	9.7	-3.7	36.6	239.8	432.4	46.4	2.4	16.4	.0	14.8	SUM-AVG
Y	4	13	24	353.4	31.4	-52.3	.0	5.6	-10.0	39.2	335.5	413.0	44.7	3.2	16.6	.1	14.1	SUM-AVG
Y	4	14	24	352.0	42.4	-16.4	.0	7.2	-1.1	42.4	409.6	422.4	43.0	4.1	17.8	.0	14.3	SUM-AVG
Y	4	15	24	391.7	73.3	26.6	.0	9.7	-3.0	53.3	526.9	427.7	43.4	5.2	19.1	-.0	14.5	SUM-AVG
Y	4	16	24	461.9	98.0	37.8	.0	11.6	11.0	31.1	278.7	295.3	44.9	9.5	19.1	-.1	10.2	SUM-AVG
Y	4	17	24	528.1	129.2	83.5	.0	16.0	-3.7	45.3	231.6	354.2	46.8	7.2	18.8	-.1	12.0	SUM-AVG
Y	4	18	24	271.3	.5	-95.6	.0	3.3	-6.2	35.6	393.9	442.2	47.0	3.5	17.9	.1	14.9	SUM-AVG
Y	4	19	24	416.9	55.8	.5	.0	9.5	6.6	28.4	363.3	440.8	44.9	2.7	17.1	-.0	15.0	SUM-AVG
Y	4	20	23	543.9	111.4	74.9	.0	14.2	9.7	30.0	228.3	405.7	46.2	2.8	16.6	-.1	14.4	SUM-AVG

TABLE 6

DAILY SUMMARY

DAILY PERFORMANCE SUMMARY FOR SHERIDAN HOUSE (ID='II')

UNITS: ENERGY-MJ,TEMPERATURE-DEG C

REC#	MO	DAY	HR	SOLAR INSO	COLL OUTPT	STORE OUTPT	STORE HOUSE	DHWC OUTPT	DELTA DHW	ELECT POWER	FURNC DUCT	HOUSE LOAD	STORE TEMP	AMBNT TEMP	HOUSE TEMP	STORE LOSS	DEGRE HOUR	
DAY	4	21	19	780.8	213.2	164.1	20.1	22.9	-.8	54.0	270.5	282.8	52.7	5.6	17.2	-.2	11.6	SUM-AVG
DAY	4	22	32	547.9	23.6	-263.3	71.9	7.7	-17.2	50.6	308.3	522.4	48.8	5.1	17.8	.2	13.1	SUM-AVG
DAY	4	24	25	623.4	167.7	15.7	111.8	20.8	17.2	52.7	167.8	416.4	44.5	5.3	18.3	-.0	13.5	SUM-AVG
DAY	4	25	24	312.3	-.1	-56.6	.0	4.6	-4.8	32.9	381.0	351.5	43.1	7.1	18.5	.1	12.0	SUM-AVG
DAY	4	26	24	833.8	259.7	272.6	8.5	27.4	10.6	47.9	229.4	304.7	46.9	8.8	18.7	-.4	10.4	SUM-AVG
DAY	4	27	24	848.3	244.9	174.8	6.4	24.7	3.5	38.6	107.7	291.6	56.0	9.8	19.3	-.2	9.9	SUM-AVG
DAY	4	28	24	856.3	228.3	87.8	28.1	25.9	4.7	42.7	.0	237.8	61.3	11.4	19.2	-.1	8.2	SUM-AVG
DAY	4	29	24	639.2	146.3	-39.7	40.9	17.0	-12.2	46.5	.0	275.6	62.8	9.8	18.8	.0	9.3	SUM-AVG
DAY	4	30	24	435.4	46.1	-195.1	102.0	10.0	-1.2	39.9	.0	316.3	57.8	8.8	19.0	.2	10.7	SUM-AVG
DAY	5	1	24	447.3	47.4	-52.1	.0	9.9	-2.0	30.8	91.2	301.7	53.4	8.4	18.2	.0	10.3	SUM-AVG
DAY	5	2	24	799.4	213.0	179.4	.0	25.5	14.8	37.7	141.3	306.2	55.2	7.8	17.8	-.2	10.4	SUM-AVG
DAY	5	3	24	856.3	211.7	114.7	.0	24.8	9.8	35.2	113.4	262.5	61.4	9.5	18.0	-.1	9.0	SUM-AVG
DAY	5	4	11	38.4	.0	-80.2	.0	.0	-11.8	15.6	137.7	147.3	62.8	8.0	18.4	.1	11.3	SUM-AVG
DAY	5	11	3				8.1	.0	-10.8			38.5	45.0	7.8	17.9		13.8	SUM-AVG
DAY	5	12	24	668.4	177.9	158.7	.0	19.0	5.9	35.4	94.1	228.7	47.9	9.6	17.0	-.2	8.0	SUM-AVG
DAY	5	13	24	415.6	44.8	-78.5	22.0	9.9	-9.9	48.3	80.2	229.7	49.2	9.9	17.4	.1	7.8	SUM-AVG
DAY	5	14	24	657.8	168.5	134.2	.0	21.9	2.0	44.9	50.5	188.5	50.5	11.9	18.1	-.2	6.5	SUM-AVG
DAY	5	15	24	644.5	147.1	64.7	.0	19.3	7.9	37.0	159.7	242.4	54.7	11.5	19.4	-.1	8.2	SUM-AVG
DAY	5	16	23	229.0	.0	-49.0	37.0	2.0	-14.8	38.8	.0	269.7	55.7	10.3	19.4	.1	9.5	SUM-AVG
DAY	5	17	24	633.9	132.4	54.5	.0	18.3	18.9	30.6	85.0	234.2	55.2	11.1	18.8	-.1	8.0	SUM-AVG
DAY	5	18	24	514.8	93.3	-1.9	1.3	13.3	-6.8	30.0	.0	192.9	56.2	11.5	17.8	-.0	6.6	SUM-AVG
DAY	5	19	24	890.7	241.0	177.9	.0	28.7	23.5	33.8	.0	183.0	59.5	11.6	17.5	-.2	6.2	SUM-AVG
DAY	5	20	24	778.2	167.0	36.2	.0	20.7	-15.2	39.9	.0	147.5	63.9	13.1	17.9	-.0	5.1	SUM-AVG
DAY	5	21	24	848.3	207.1	68.5	25.7	25.5	9.7	33.9	.0	152.3	65.9	15.7	20.6	-.1	5.2	SUM-AVG
DAY	5	22	24	880.1	217.5	63.3	29.9	25.5	-.8	37.7	.0	185.3	68.5	15.5	21.5	-.1	6.2	SUM-AVG
DAY	5	23	24	815.3	187.2	40.9	.0	23.5	2.1	39.3	.0	121.7	71.2	17.0	21.0	-.1	4.2	SUM-AVG
DAY	5	24	24	270.0	-1.6	-202.2	.0	3.1	-20.8	26.7	.0	194.1	68.2	13.0	19.4	.2	6.5	SUM-AVG
DAY	5	25	24	884.1	219.3	130.4	.0	29.1	13.6	33.6	100.4	153.4	66.3	13.5	18.5	-.1	5.3	SUM-AVG
DAY	5	26	24	831.1	180.1	44.2	.0	23.9	21.6	27.9	.0	114.4	70.0	16.4	20.1	-.1	3.9	SUM-AVG
DAY	5	27	24	566.4	73.1	-116.1	11.9	9.6	-29.2	34.8	.0	254.2	68.7	12.0	20.2	.1	8.4	SUM-AVG

TABLE 7

DAILY SUMMARY

AILY PERFORMANCE SUMMARY FOR SHERIDAN HOUSE (ID='III')

NITS: ENERGY-MJ,TEMPERATURE-DEG C

W	MO	DAY	HR	SOLAR INSO	COLL OUTPT	STORE OUTPT	STORE HOUSE	DHWC OUTPT	DELTA DHW	ELECT POWER	FURNC DUCT	HOUSE LOAD	STORE TEMP	AMBNT TEMP	HOUSE TEMP	STORE LOSS	DEGRE HOUR	
'	5	28	22	471.2	7.9	-221.5	74.5	7.8	-14.0	45.2	.0	349.2	60.8	6.3	18.7	.2	12.4	SUM-AVG
'	5	29.	24	595.6	81.7	-78.7	67.7	15.7	3.1	40.0	113.0	376.1	55.3	5.2	17.5	.1	12.8	SUM-AVG
'	5	30	24	596.9	99.2	-25.5	55.6	15.0	3.2	37.6	106.0	323.0	54.3	6.7	17.2	.0	11.0	SUM-AVG
'	5	31	24	743.8	182.9	143.7	13.7	22.8	9.1	40.9	172.3	281.4	55.6	9.9	19.1	-.1	9.6	SUM-AVG
'	6	1	24	583.6	126.7	43.3	.0	17.6	8.0	29.4	158.1	258.8	58.7	10.7	19.1	-.1	8.8	SUM-AVG
'	6	2	24	819.2	227.5	109.4	45.9	26.2	11.0	40.2	.0	160.4	61.3	15.3	20.5	-.1	5.6	SUM-AVG
'	6	3	24	845.7	205.4	96.8	.0	23.4	-11.7	34.7	.0	126.3	66.1	17.5	21.7	-.1	4.3	SUM-AVG
'	6	4	24	524.1	37.4	-147.7	5.3	11.3	-7.0	32.0	1.1	122.5	65.2	16.6	20.6	.1	4.2	SUM-AVG
'	6	5	24	173.4	.0	-139.4	.0	2.0	-16.3	35.9	.0	154.6	59.6	14.5	19.5	.1	5.2	SUM-AVG
'	6	6	24	352.0	10.2	-196.2	96.6	7.0	-1.3	35.6	40.3	314.4	52.7	8.4	18.6	.2	10.5	SUM-AVG
'	6	7	24	602.2	136.7	54.5	55.3	20.4	16.6	43.3	140.4	341.4	49.1	7.2	18.3	-.1	11.5	SUM-AVG
'	6	8	24	700.1	177.9	113.2	24.5	20.8	-3.2	42.9	216.6	305.9	52.9	9.1	19.1	-.1	10.4	SUM-AVG
'	6	9	24	885.4	247.5	188.9	.0	26.2	22.3	29.7	.0	172.0	58.8	13.3	18.9	-.2	6.0	SUM-AVG
'	6	10	24	810.0	200.9	83.5	.0	23.8	-3.4	33.5	.0	143.4	64.6	16.6	21.3	-.1	4.9	SUM-AVG
'	6	11	24	810.0	196.7	61.8	.0	22.1	5.6	27.9	.0	99.1	67.5	19.3	22.5	-.1	3.4	SUM-AVG
'	6	12	24	866.9	211.1	74.2	.0	24.4	1.5	30.7	.0	118.2	70.3	19.7	23.5	-.1	4.0	SUM-AVG
'	6	13	24	868.2	176.0	8.3	.0	21.6	-9.6	33.5	.0	159.3	72.2	17.0	22.2	-.0	5.4	SUM-AVG
'	6	14	24	798.1	146.0	-35.4	.0	19.3	11.5	26.7	23.6	167.3	71.8	12.9	18.3	.0	5.7	SUM-AVG
'	6	15	24	807.3	154.3	-16.7	.0	30.6	-2.5	26.8	26.4	150.7	70.7	12.4	17.3	.0	5.1	SUM-AVG
'	6	16	24	836.4	179.7	29.7	.0	26.0	-1.0	31.2	13.1	125.2	70.7	14.5	18.6	-.0	4.3	SUM-AVG
'	6	17	24	173.4	.0	-192.0	.0	.5	-27.1	31.3	.0	150.9	67.9	14.4	19.3	.2	5.1	SUM-AVG
'	6	18	24	72.8	.0	-221.9	75.4	.0	-15.0	38.6	58.8	226.1	60.3	10.1	17.5	.2	7.6	SUM-AVG

TABLE 8

SOLAR HEATING SUMMARY FOR 78 DATA DAYS, 3/20 TO 6/18

	MJ	MBTU	%
Total Solar Insolation	44,663	47.1	100
Solar Collected and Stored	9,077	9.58	20
Solar to House	1,628	1.72	3.6
Lost from Storage	7,449	7.86	
House Heat Load	24,252	25.59	100
(1) Furnace Heat	14,302	15.09	59
(2) Electric Dissipation	1,806	1.91	8
Solar Heat Delivered	1,628	1.72	7
(3) Wood	6,516	6.87	26
Average House Temperature	18.5°C	65.3°F	

(1) Approximated ($\pm$18%)

(2) Assuming .6 of total electricity dissipated as heat inside house

(3) Estimated from heat balance considerations

TABLE 9

SOLAR HOT WATER SUMMARY FOR 78 DATA DAYS

(1) Total DHW Insolation	4218 MJ/m^2	(1) Estimated from insolation measured at collector array.
Total Collector Output	1178 MJ	
(2) DHW Tank Loss (15%)	177 MJ	(2) Heat "loss" goes into insulated basement
(3) Daily Average Output	15 MJ	(3) 15 MJ/day is enough to heat 20.4 gallons each day from 50°F to 135°F.
Average Collection Efficiency	28%	
Average System Efficiency	24%	

TABLE 10

PREDICTED SOLAR RADIATION AT SHERIDAN SITE, kWh/m^2-day

	(1) Missoula @ 60° Data	45°/60° Factor ASHRAE	Predicted @ 45°	Measured @ 45° On Site
April	3.59	1.07	3.84	3.65
May	4.15	1.11	4.60	4.79
(2) June	4.55	1.13	5.14	4.69

(1) Montana Solar Data Manual, 1980 edition

(2) Two weeks data

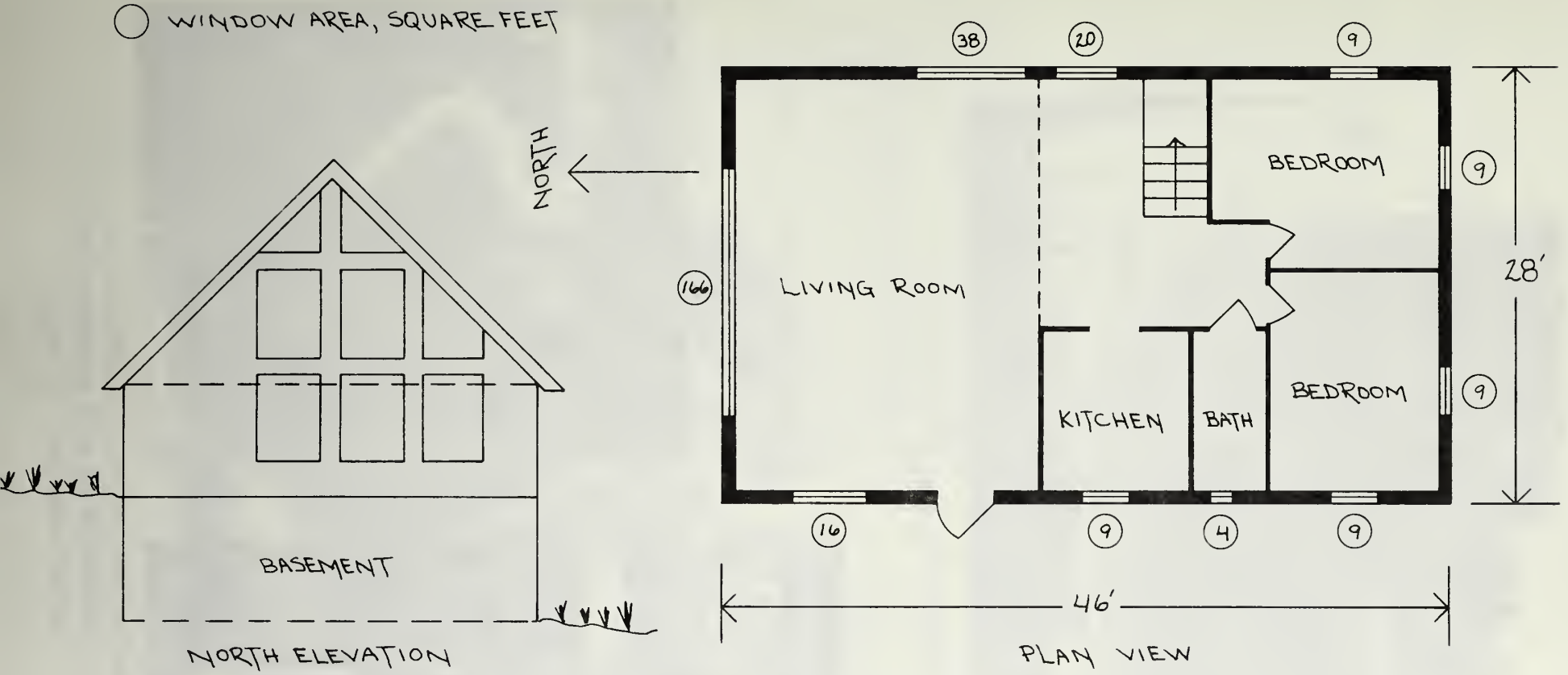
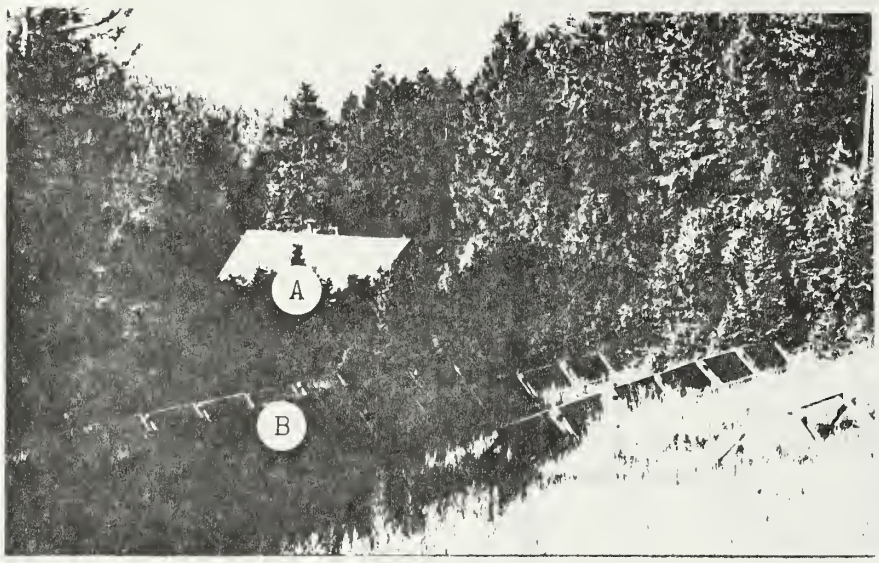


Figure 2: Sketch of Sheridan residence showing window areas



(A) House

(B) Collector Array

(C) Distribution Manifold

(D) Collector Flow - To and from house.

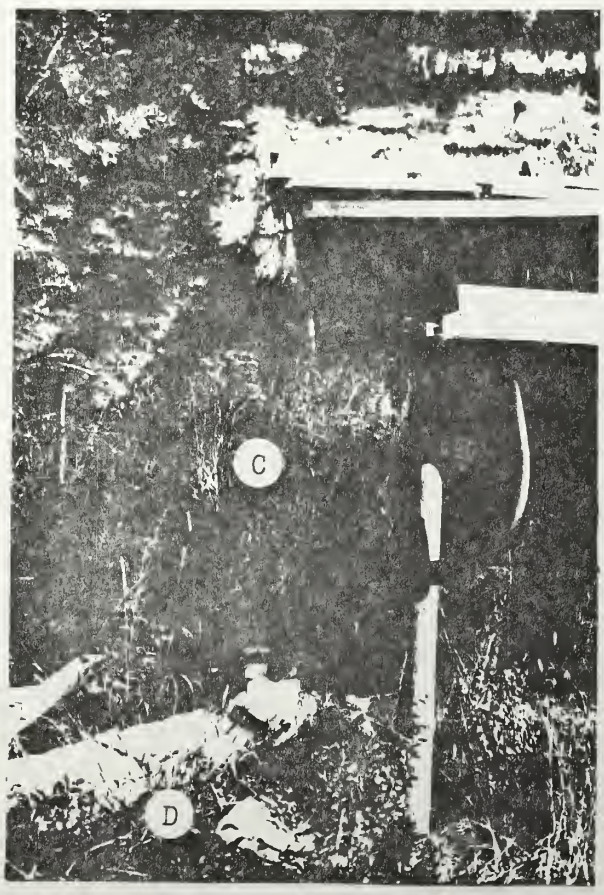
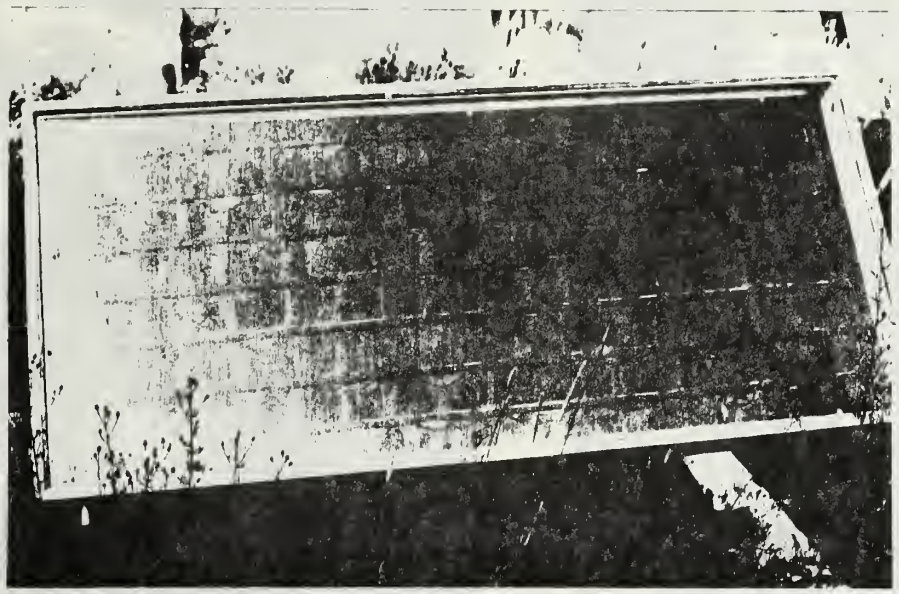
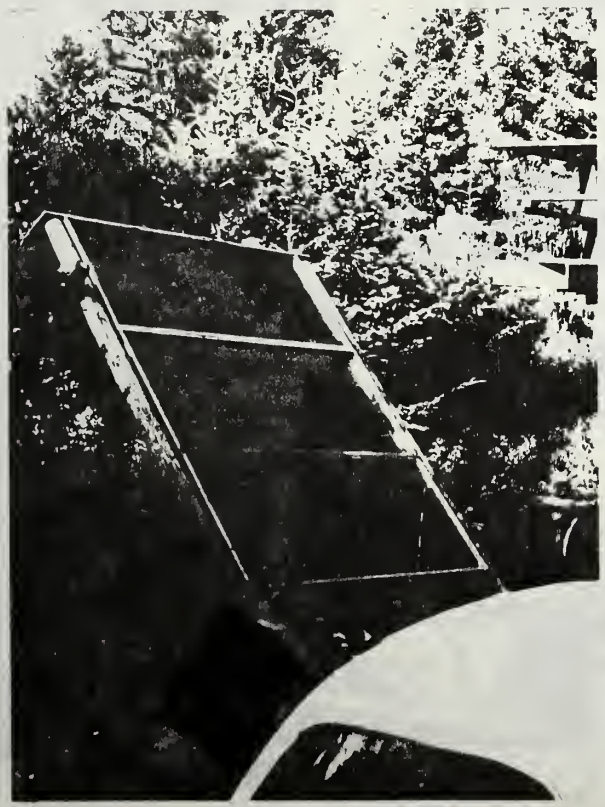


Figure 3: Photographs of main collector array

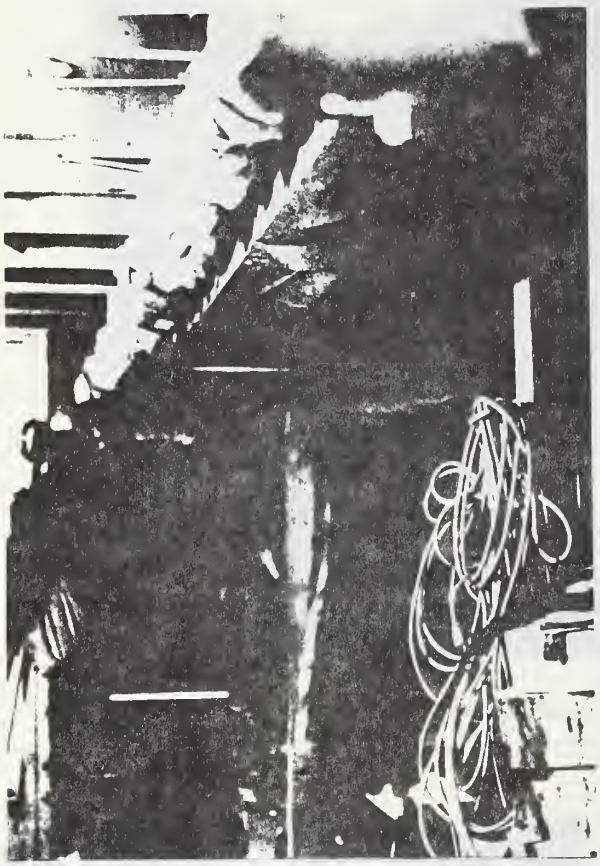


(a) Close-up of collector panel

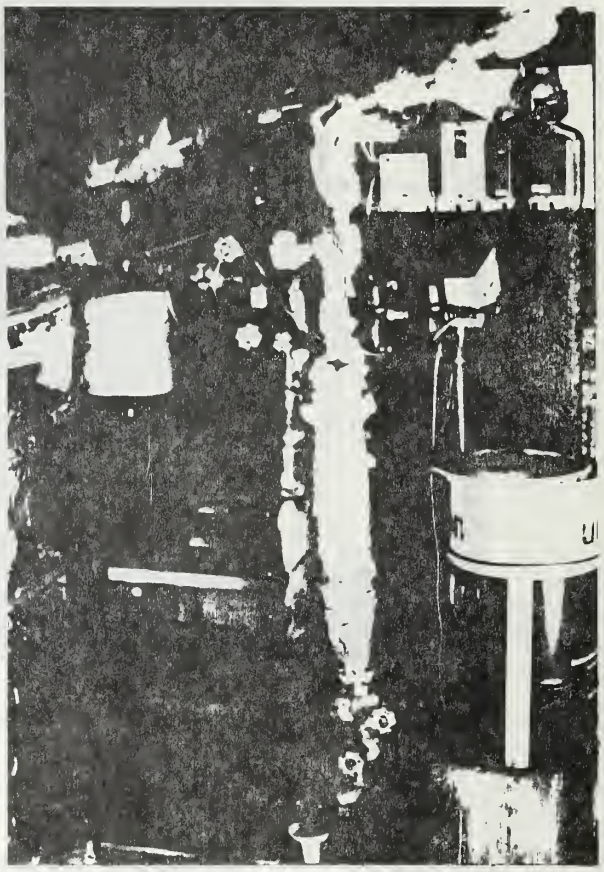


(b) Domestic hot water (DHW) collector

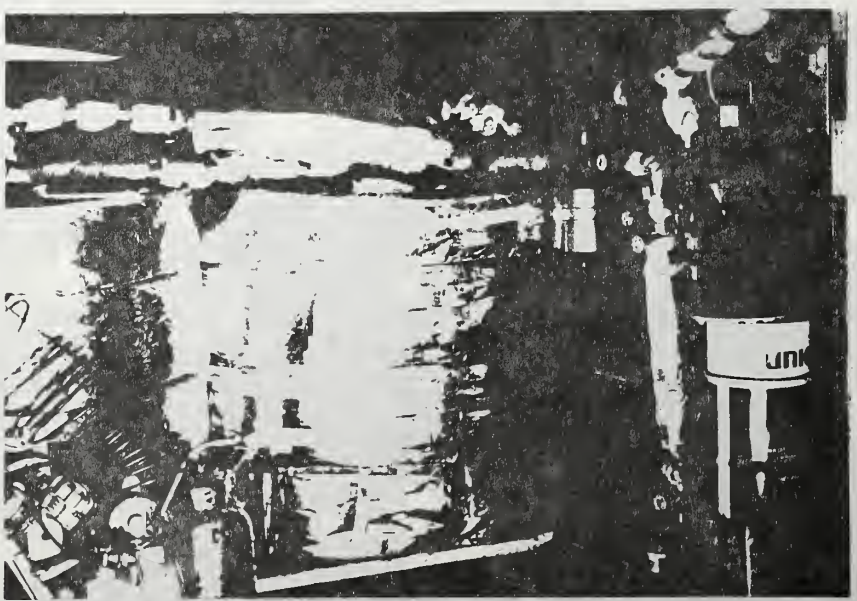
Figure 4: Collector panels



(a) Storage to house exchanger in duct



(b) Pumps and controls



(c) Insulated heat storage tanks

Figure 5: Heat storage system and controls, located in basement

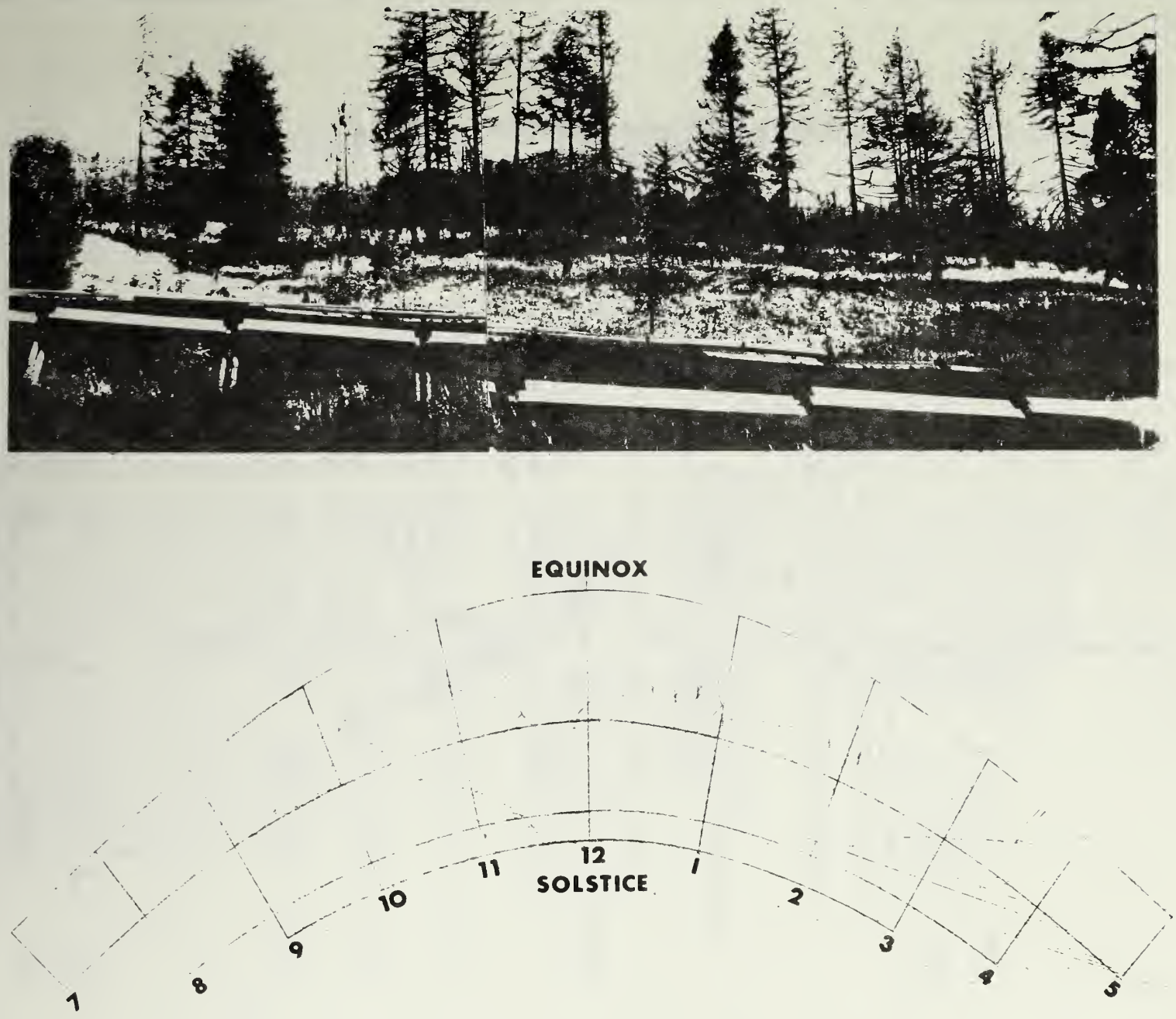


Figure 6: Shading diagram showing exposure of collector field to the sun during the winter

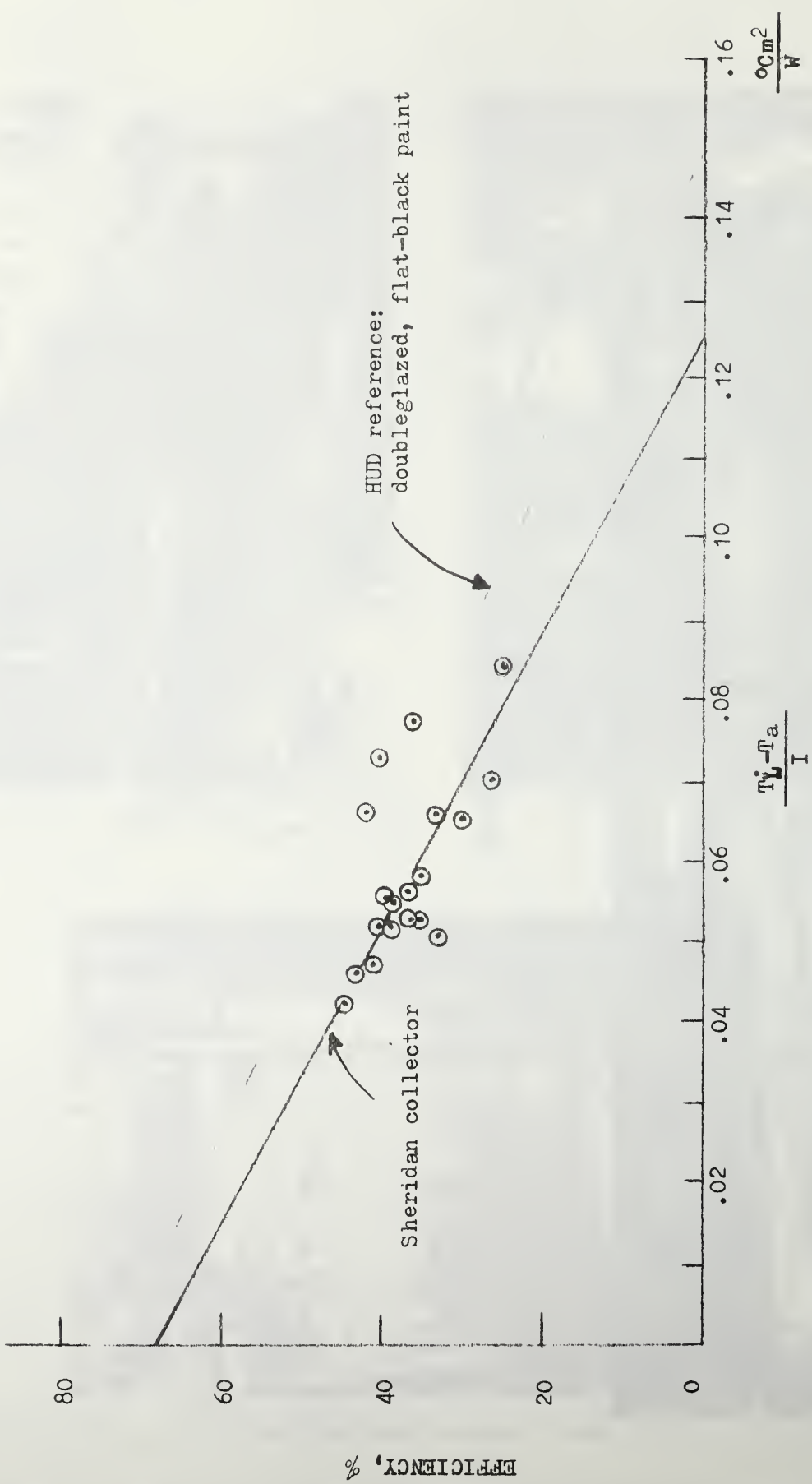


Figure 7: Collector efficiency curves

```
3000REM SUBR *** COMPUTE HOURLY SUMS
3005 !"-- SUMMING"
3010 N0=N0+1\REM #HRS
3012 REM  ALL THE FOLLOWING ARE IN MEGA JOULES
3015 S(1)=D(2)*.97*37.9*3.6    \REM SOLAR INPUT
3018 REM TEMPERATURES ZEROED ON STATUS, GLYCOL MIXTURE
3020 S(2)=D(5)*2.089*3.4*(D(20)-D(16))/(D(5)+.0001)  \ REM COLL TO STORAGE
3030 S(3)=5.677*4.19*(D(12)-T1)  \REM MAIN STORAGE HEAT CHANGE
3040 S(4)=D(6)*4.19*0.587*(D(15)-D(19))/(D(6)+.0001)  \REM STORAGE TO HOUSE
3050 S(5)=D(7)*0.250*3.4*(D(17)-D(13))/(D(7)+.0001)  \REM DHW COLLECTORS OUT
3060 S(6)=0.405*4.19*(D(18)-T2)   \REM HOT WATER TANK HEAT CHANGE
3070 S(7)=(D(3)+D(4))*3.6*.114 \REM ELECTRICAL POWER, TOTAL CORRECTED
3071 S(8)=0\IF(D(11)-D(10))>0THEN 3072 ELSE 3073
3072 S(8)=2*(D(11)-D(10))*.7\REM ESTIMATED AIR DUCT OUTPUT,CORRECTED
3073 V9=D(12)-(D(9)+0.5*D(10))/1.5
3074 S(13)=-S(3)/V9   \ REM STORAGE LOSS FACTOR
3076 S(9)=1.28*(D(10)-D(9))  \REM CALCULATED HOUSE HEAT LOAD
3080 T1=D(12)\T2=D(18) \ REM SAVE TEMPERATURES FOR STORAGE DIFFERENCES
3085 S(10)=D(12)\S(11)=D(9)\S(12)=D(10)\REM TEMPERATURES
3090 S(14)=D(10)-D(9)
3140 FOR I=1 TO 14\T(I)=T(I)+S(I)\REM SUM FOR DAY, PRINT HR DATA
3150 NEXT
3160 S8=S(10)\S9=S(12)\RETURN   \REM SAVE FOR TEMP DIFFERENCE - TUBE&HOUSE
3200REM *** CALC AVERAGES & FINAL QUANTITIES
3210 FOR I=10TO 14\ REM AVERAGE TEMPERATURES (NOTE HEATS NOT INCL.,)
3220 T(I)=T(I)/N0\REM DAILY AVGS = SUM / NR HRS
3230 NEXT\RETURN
3400REM SUBR *** PRINT REPORT HEADING
3405 '#1\!#1"  DAILY PERFORMANCE SUMMARY FOR SHERIDAN HOUSE (ID='",R$,"')"
3406 '#1\!#1"  UNITS: ENERGY-MJ,TEMPERATURE-DEG C"
3410 '#1\'#1,"REC# MO DAY  HR ",TAB(16),
3420 '#1," SOLAR  COLL   STORE  STORE  DHWC  DELTA  ELECT   FURNC   HOUSE",
3430 '#1," STORE  AMBNT  HOUSE  STORE  DEGRE"
3440 !#1,TAB(16),
3450 '#1," INSO   OUTPT  OUTPT  HOUSE  OUTPT  DHW   POWER   DUCT    LOAD ",
3460 '#1, " TEMP   TEMP   TEMP   LOSS  HOUR  "
3470 '#1,TAB(16),
3495 RETURN
```

Figure 8: Computer program of heat flow equations used for performance summary

DAILY PERFORMANCE SUMMARY FOR SHERIDAN HOUSE (ID='II')

UNITS: ENERGY-MJ,TEMPERATURE-DEG C

REC#	MO	DAY	HR	SOLAR INSO (1)	COLL OUTPT (2)	STORE OUTPT (3)	STORE HOUSE (4)	DHWC OUTPT (5)	DELTA DHW (6)	ELECT POWER (7)	FURNC DUCT (8)	HOUSE LOAD (9)	STORE TEMP (10)	AMBNT TEMP (11)	HOUSE TEMP (12)	STORE LOSS (13)	DEGRE HOUR (14)

DESCRIPTION

(1) The total solar radiation intercepted by the collectors, mega joule.

(2) The energy collected and delivered to the storage tank, mega joule.

(3) The change in energy of the heat storage system. This quantity is negative when heat is being added to storage, mega joule.

(4) Solar heat delivered from storage to the house, mega joule.

(5) Solar heat delivered to DHW tank, mega joule.

(6) Change in energy of DHW storage tank, mega joule.

(7) Total electric power flowing into home, mega joule.

(8) Auxiliary heat from furnace (approximate), mega joule.

(9) House heat load based on actual degree-hours and 1.28 MJ/°C hr, mega joule.

(10) Temperature of heat storage, degrees Celsius.

(11) Temperature of ambient air, measured in degrees Celsius.

(12) Temperature of house air, measured in degrees Celsius.

(13) Heat storage average loss coefficient when (2)=(4)=0.

(14) Temperature difference between house and outside air, degrees Celsius.

Note on units: 1 BTU = 1.055 kJ; 10,000 BTU = 10.55 MJ

Figure 9: Table headings for performance summary

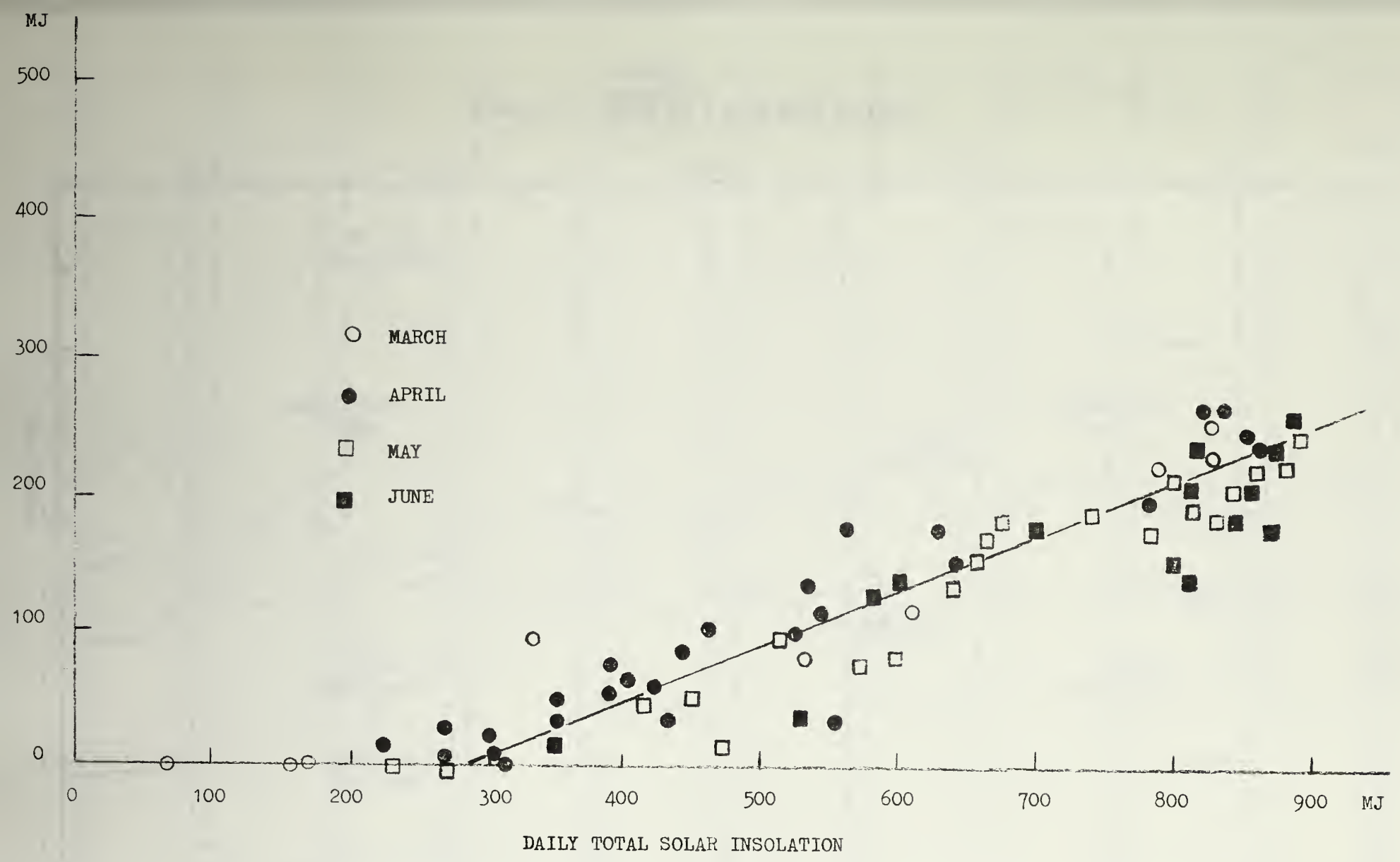


Figure 10: Sheridan collector performance curve

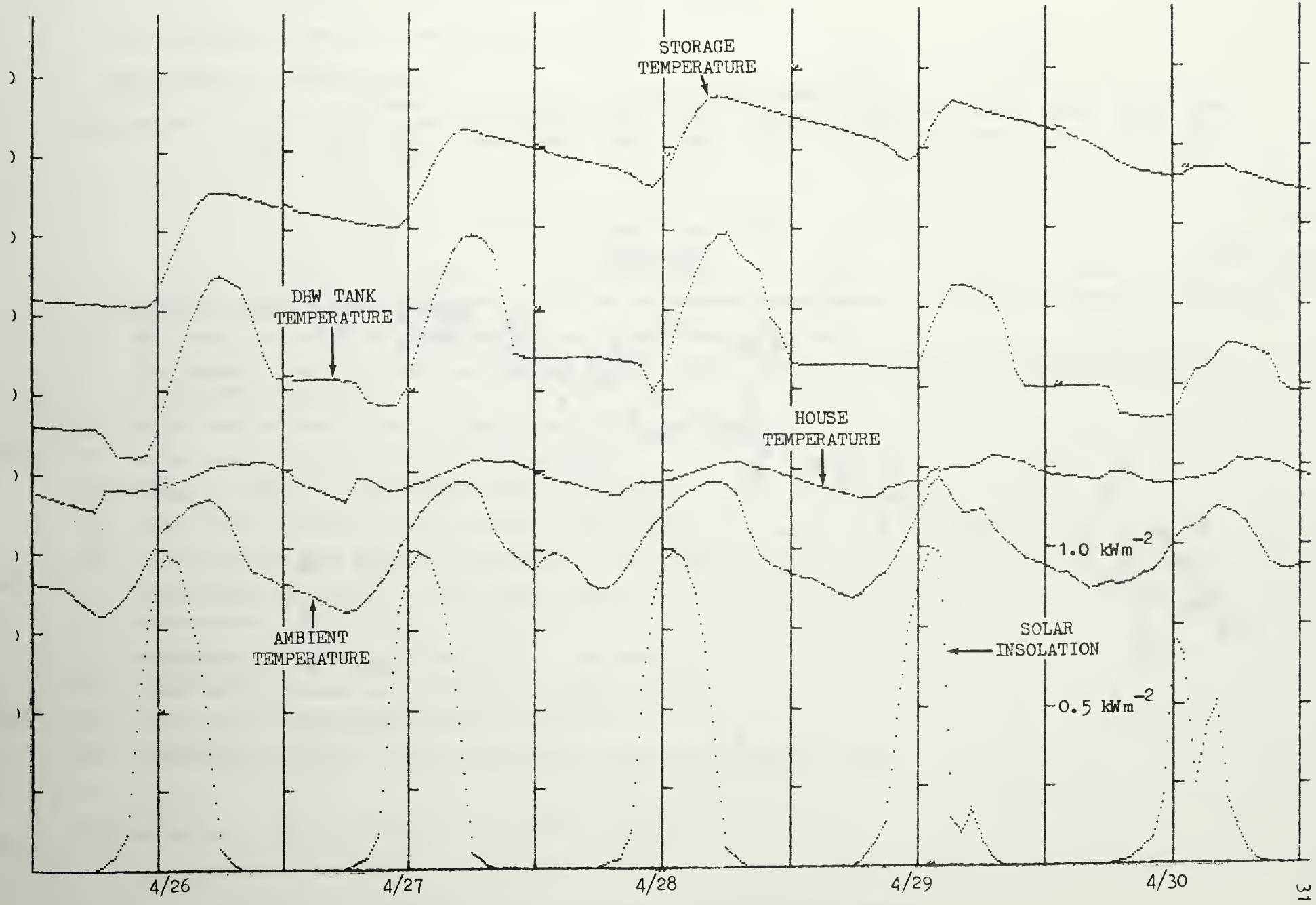


Figure 11: Graph of 5 Days Data in April

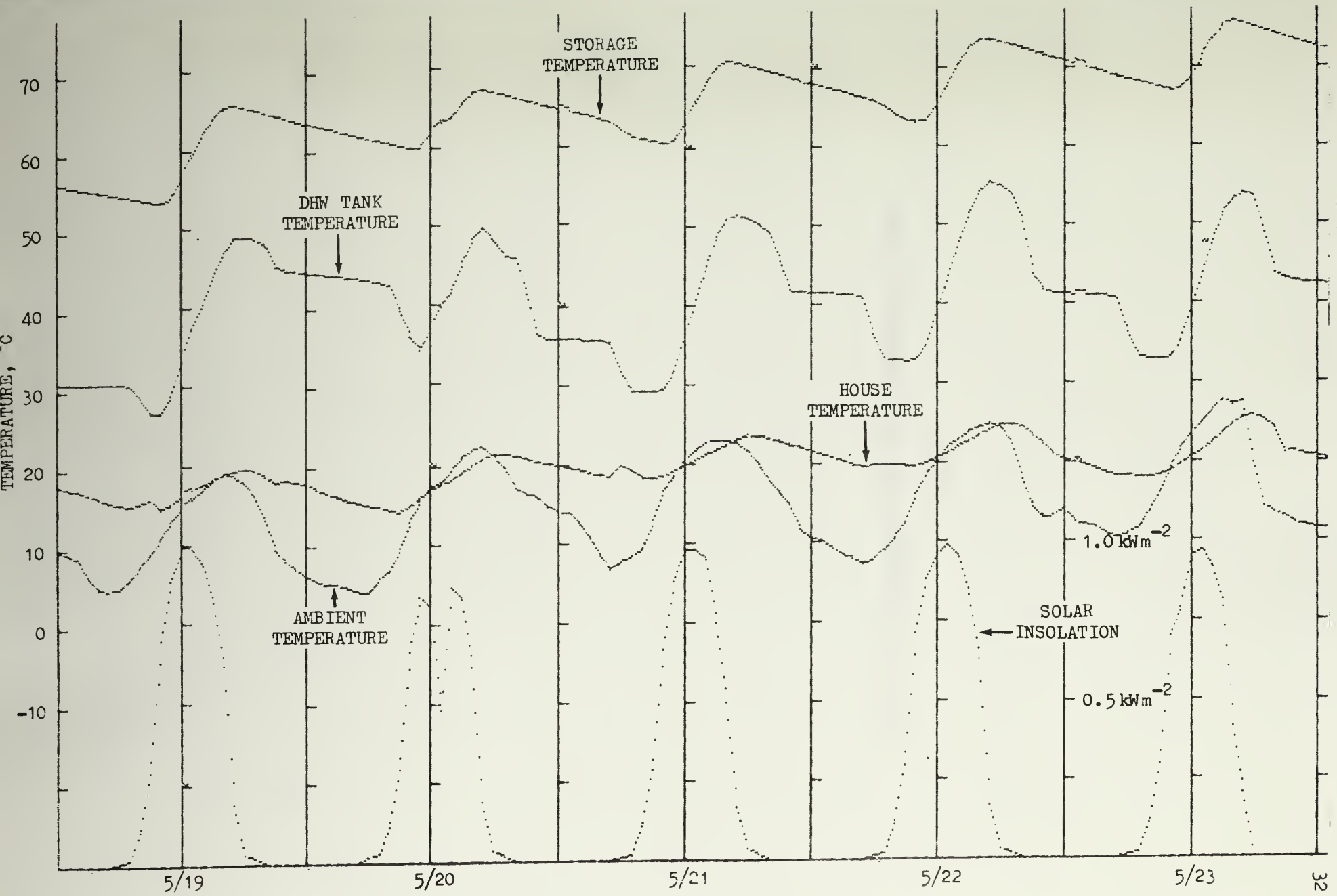


Figure 12: Graph of 5 Days Data in May

APPENDIX I

HOURLY PERFORMANCE DATA FOR SHERIDAN SOLAR SYSTEM

TABLE 1

DAILY PERFORMANCE SUMMARY FOR SHERIDAN HOUSE (ID='II')

UNITS: ENERGY-MJ,TEMPERATURE-DEG C

REC#	MO	DAY	HR	SOLAR INSO	COLL OUTPT	STORE OUTPT	STORE HOUSE	DHWC OUTPT	DELTA DHW	ELECT POWER	FURNC DUCT	HOUSE LOAD	STORE TEMP	AMBNT TEMP	HOUSE TEMP	STORE LOSS	DEGRE HOUR	
77	4	25	1	.0	.0	-2.6	.0	.0	-.1	.8	.0	17.7	44.3	4.7	18.5	.1	13.8	
78	4	25	2	.0	.0	-3.1	.0	.0	-.2	.8	.0	17.6	44.2	4.2	17.9	.1	13.8	
79	4	25	3	.0	.0	-2.9	.0	.0	-.3	.4	.0	18.4	44.1	3.1	17.5	.1	14.4	
80	4	25	4	.0	.0	-3.1	.0	.0	-.0	.7	.0	17.7	44.0	3.1	16.9	.1	13.8	
81	4	25	5	.0	.0	-2.9	.0	.0	-.2	.4	.0	16.7	43.8	3.4	16.4	.1	13.0	
82	4	25	6	.0	.0	-3.1	.0	.0	-.1	.5	.0	16.1	43.7	3.3	15.9	.1	12.6	
83	4	25	7	.0	.0	-3.1	.0	.0	-.2	.7	.0	15.9	43.6	3.1	15.5	.1	12.4	
84	4	25	8	2.6	.0	-2.9	.0	.0	-.3	3.7	57.6	19.1	43.5	3.4	18.4	.1	15.0	
85	4	25	9	6.6	.0	-1.9	.0	.0	-3.1	4.0	39.8	18.8	43.4	4.3	19.0	.1	14.7	
86	4	25	10	18.5	.0	-2.6	.0	.0	-.6	1.1	37.9	16.8	43.3	5.7	18.9	.1	13.1	
87	4	25	11	14.6	.0	-2.4	.0	.0	-.2	1.0	36.3	16.1	43.2	6.1	18.7	.1	12.6	
88	4	25	12	31.8	.0	-2.6	.0	.2	-.1	1.1	37.6	16.1	43.1	6.4	18.9	.1	12.6	
89	4	25	13	47.6	.0	-1.9	.0	1.1	.1	.9	29.1	12.9	43.0	9.1	19.2	.1	10.1	
90	4	25	14	29.1	.0	-1.0	.0	.4	.7	1.2	31.1	12.1	42.9	9.8	19.3	.0	9.5	
91	4	25	15	35.7	.0	-1.9	.0	.5	1.1	.8	21.4	10.9	42.9	10.7	19.2	.1	8.5	
92	4	25	16	33.1	-.7	-1.7	.0	.7	1.5	1.1	20.9	10.2	42.8	11.4	19.4	.1	8.0	
93	4	25	17	39.7	.6	-1.7	.0	.4	1.0	1.0	20.2	9.5	42.7	12.0	19.5	.1	7.4	
94	4	25	18	35.7	.0	-1.9	.0	1.1	1.5	.7	16.1	8.9	42.6	12.8	19.8	.1	7.0	
95	4	25	19	11.9	.0	-1.7	.0	.1	1.1	1.7	.0	10.2	42.6	11.8	19.7	.1	8.0	
96	4	25	20	5.3	.0	-2.1	.0	.0	-.4	1.7	.0	12.0	42.5	10.3	19.7	.1	9.4	
97	4	25	21	.0	.0	-2.4	.0	.0	-.3	.6	.0	13.4	42.4	9.0	19.4	.1	10.4	
98	4	25	22	.0	.0	-1.9	.0	.0	-4.6	4.5	12.5	13.9	42.3	8.3	19.2	.1	10.9	
99	4	25	23	.0	.0	-2.4	.0	.0	-1.4	2.8	20.2	15.2	42.2	7.3	19.1	.1	11.9	
100	4	26	0	.0	.0	-3.1	.0	.0	.0	.8	.1	15.2	42.1	6.4	18.3	.1	11.9	
DAY	4	25	24	312.3	-.1	-56.6	.0	4.6	-4.8	32.9	381.0	351.5	43.1	7.1	18.5	.1	12.0	SUM-AVG

THERMAL PERFORMANCE
OF THE SALYER SOLAR HOUSE

by

Charless W. Fowlkes

FOWLKES ENGINEERING
31 Gardner Park Drive
Bozeman, MT 59715

for

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
RENEWABLE ALTERNATIVE ENERGY SOURCES PROGRAM

John Orndorff, Bureau Chief

NOTICE

This report was prepared as an account of work sponsored by the Energy Division of the Montana Department of Natural Resources and Conservation through the Alternative Renewable Energy Sources Program. Neither the State of Montana, nor the Department, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

ABSTRACT

This project was a site-built, active-air solar system retrofit to an older residence in Hamilton, Montana. The grant application, design and execution were carried out by the District #11 Human Resources Development Council. The design goal was to produce a "low cost" system. The resulting design was unconventional in several respects: the rock bin incorporated a baffle which reduced its storage capacity by a factor of two and a damper was not used to isolate the collector loop and the house loop. These design anomalous plus numerous air leaks reduced the potential performance of this system. The system supplied negligible solar heat to the house during the monitoring period. It seems that the system sometimes removes heat from the house.

NOTE ON UNITS

The data is presented in metric units. These units are in accord with the recommendations of the International Solar Energy Society as well as most current technical journals. The overall summaries and numbers in the test have been given in dual units. The heat load calculations are presented in conventional units.

Most readers are familiar with the Celsius or Centigrade temperature scale and are also familiar with energy units of kilowatt hours. The only other metric unit which occurs frequently in this report is the Joule (J), the metric unit of energy which replaces the Btu (a Btu is equal to 1,055 Joules). The mega joule (MJ) is equal to 10^6J (100,000 Btu/hr = 105 MJ/hr).

Other abbreviations used in this report include: m = meters; m^2 = square meters; l = liters; h = hours; gph = gallons per hour; and MBtu = millions of Btu's.

TABLE OF CONTENTS

1.0 Introduction 1

2.0 Acknowledgments 1

3.0 Project Description 1

4.0 Instrumentation and Measurements

- 4.1 Transducer Layout 2
- 4.2 Flow Measurements 3
- 4.3 Flow Balance and Leaks 3
- 4.4 Data Reduction 4
- 4.5 Data Base 5

5.0 Hourly and Daily Summary of Data 5

6.0 Overall Performance Summary 6

7.0 Collector Efficiency and Shading 6

8.0 Heat Load Calculations 7

9.0 Projected Potential Performance 7

10.0 Graphical Presentation of Data 8

11.0 Conclusions 8

TABLES

Table 1 - Example of Hourly Performance Data 9

Table 2 - Overall Performance Summary of Salyer House During Monitoring Period 10

Table 3 - Calculated Heat Load Factor for Salyer House 11

Table 4 - Projected Potential Yearly Performance 12

FIGURES

Figure 1 - Salyer House Photographs 13
Figure 2 - Salyer House Photographs 14
Figure 3 - Attic of Salyer House 15
Figure 4 - Floor Plan of House and
Schematic of Collector Construction 16
Figure 5 - Schematic of Solar Heating System
Showing Instrumentation Arrangement 17
Figure 6 - Flow Profiles Resulting From
Scanning the Ducts Using A Hot Wire Anemometer 18
Figure 7 - Flow Balance and Leaks: Collector fan is on
and House fan is off 19
Figure 8 - Flow Balance and Leaks: Collector fan is on
and House fan is on 20
Figure 9 - Computer Equations for Heat Quantities 21
Figure 10 - Collector Efficiency Curves 22
Figure 11 - Winter Shading of Salyer Collector 23
Figure 12 - Daily Average Collector Performance 24
Figure 13 - Graph of 5 Days Data in January 25
Figure 14 - Graph of 5 Days Data in February 26

Appendix I - Hourly Performance Data for Salyer House Between 1/23 and 2/10

1.0 INTRODUCTION

This project is located in Hamilton, Montana and is the residence of Mrs. Pauline Salyer and her sons Jay and Robin. This house was chosen by the District #11 Human Resources Development Council to demonstrate retrofitting an older house with a solar heating system. The goal of their program was to "cut use of conventional heating energy by at least 50% in the target homes" and, thus, reduce the economic burden of rising energy costs on low-income persons.

The proposed project was submitted by Ken Boggs and Roger King and six solar systems were installed on low-income homes. Labor to build the system was supplemented with Comprehensive Employment and Training Act (CETA) workers.

2.0 ACKNOWLEDGMENTS

We gratefully acknowledge the cooperation of Mrs. Pauline Salyer during this monitoring project. Mrs. Salyer allowed us to use one of her closets to house the data acquisition system. We spent several days crawling around in the attic and crawl space measuring flow rates and locating temperature transducers. During the installation, dozens of trips were made in and out of the house and her kitchen and bedroom were often littered with instruments, probes and meters. Mrs. Salyer graciously accepted these disruptions and was always helpful.

Roger King is acknowledged for spending several hours describing the construction of the solar system.

3.0 PROJECT DESCRIPTION

Photographs of the Salyer house and the solar system are shown in Figures 1, 2 and 3. The floor plan of the house and a cutaway of the air collector construction is shown in Figure 4 and a schematic of the solar system is shown in Figure 5.

The collector is air-cooled and has a total aperture of 28.46 m^2 (309 ft^2). The collector is single glazed with tempered patio-door panels 0.3 cm (0.125 in) thick. The absorber is thin aluminum painted flat black and the panels are insulated with plastic foam, Figure 3. Air flows behind the absorber and baffles are used to distribute the flow. The panels were site-built and permanently attached to the roof. The roof faces south and is pitched at a 45^{o} angle.

The schematic, Figure 5, shows a two-fan system with a single motorized damper in the collector loop. A differential thermostat was installed to control the collector fan and damper. This control has been disabled and, during the monitoring period, the collector fan and damper were controlled by a simple thermostat located behind the solar absorber. This thermostat was set at 100°F. The house fan is controlled by a thermostat within the living space. A second thermostat in the rock bin heat storage opens the house fan circuit if the rock bin is cold, thus preventing cold storage air from entering the house.

A roof vent with a manual damper is intended for use during the summer to vent excess collector heat, Figures 2 and 5. The ductwork consists of insulated, circular flexible duct combined with sections fabricated with 2.5 cm (1 in) thick fiberglass duct board (see photographs in Figure 3).

The designer chose not to use a manufactured solar air handling unit to reduce the cost of the system. A common duct above the ceiling, Figures 3 and 5, is intended to be a cold air supply to the collectors as well as a cold air return from the house. There is no damper to positively close off the house loop which may explain the unconventional baffle in the top of the rock bin, Figure 5.

Auxiliary heat is supplied to the house by a circulating natural gas heater controlled by an integral thermostat. This heater is located in the dining room, Figure 4. There is also a wood stove on the enclosed porch next to the kitchen which is used for supplementary heat.

4.0 INSTRUMENTATION AND MEASUREMENTS

4.1 Transducer Layout

The transducer layout is shown in Figure 5. Solar insolation was measured in the plane of the collectors (45°) at mid-point of the western edge of the array. The ambient temperature was measured by a shaded transducer on the north side of the house and about 3 m (10 ft) above the ground. Two temperature probes were mounted inside the house and one was placed in the attic.

The solar collectors had two independent probes in both the inlet and outlet ducts near the collectors. Two probes were used to provide backup as well as a check point on this important measurement. The rock bin-to-house loop had inlet and outlet duct probes to measure stored solar heat entering the house. A status relay was connected to each fan to record when

the fan was running. The computer program contained logic to zero the duct temperatures if the fan was off. This allows calculation of the true duct temperature while the fan is running in a cyclic mode.

A temperature probe was inserted in the hot end of the rock bin storage. Another probe was suspended in the insulated, unheated shed which contains the rock bin. The total electric power was monitored with clamp-on ammeters. These readings were calibrated against the service meter.

The heat output of the free standing wood stove and auxiliary natural gas heater could not be accurately monitored. The normal way to monitor this type of heating device is to enclose it in a calorimeter room. This can be done in a laboratory, but not in an occupied residence. Readings of the natural gas meter during the test period allowed calculation of the average auxiliary heat.

4.2 Flow Measurements

Figure 6 shows some typical results of measurements of the air flow in the ducts. A hot-wire anemometer was used to measure the mass-flow velocity at a network of points on the cross section of each duct. These results were then integrated to yield net flow through the duct.

To check the overall accuracy of the technique, the flow was measured at the collector fan inlet and outlet for one mode. Figure 6 shows that these results compare within 7%. This is considered as satisfactory agreement considering the turbulence and short lengths of duct at the measurement stations.

4.3 Flow Balance and Leaks

Probably the most significant result of this monitoring effort is shown in Figures 7 and 8. In Figure 7 the collector fan was on and the house fan was off. The numbers by the arrows are volumetric flow rates in cubic meters per minute (m^3/min). The numbers represent measurements except when enclosed in parentheses. The enclosed numbers are leakage flows necessary to balance the measured flow rates.

Looking first at the rock bin heat storage box we see that 13.2 m^3/min are flowing into the top of the box. Ideally, this same flow should be leaving the bottom of the box and proceeding back up the cold air return duct to the collectors. Measurements show that only 0.8 m^3/min is returning through the cold air duct and that 3.7 m^3/min is flowing through the house

duct. Flow balance of the inputs and outputs of the rock storage imply that 8.6 m^3/min is leaking out of the storage bin.

Looking at the collector array in Figure 7, we measured a flow of 2.2 m^3/min leaking through the summer vent (which should be closed). The flow in the return vents in the ceiling of the living room and bedroom was measured as approximately 4 to 6 m^3/min. These flows should also be zero. Flow balance on the collector implies that leaks amounting to about 4.2 m^3/min exist in the collectors and/or their ducting.

Figure 8 shows results of another set of measurements of the flows in the duct system with both collector and house fans on. These measurements were more approximate than those of Figure 7. The main conclusions of this measurement set are that (1) large rock bin and house/collector leakages exist, and (2) there is almost no flow in the collector cold air return.

It appears that the pressure drop through the thickness of the rock bin is much greater than the pressure drop across the internal baffle. The air that enters the rock bin either leaks out or flows around the baffle and into the house.

4.4 Data Reduction

The existence of the unexpected and unusual flow patterns and large leaks in this system makes precise analysis of the data impossible. When the collector is presumably storing heat in the rock bin and there is presumably no flow through the house we find that collector air that is not lost due to leakage is actually short-circuiting through the house. The collector itself which should be drawing air from the rock bin is actually drawing in air from (a) the house, (b) the summer vent, and (c) some place else, probably distributed leaks.

Collector efficiency is defined in terms of a device which has one inlet and one outlet. This collector seems to be drawing air from at least four separate sources.

As a "best effort" attempt to analyze the data, a weighted average collector inlet temperature was created based on the flow pattern in Figure 7; 16% was assumed to be at ambient temperature, 32% at attic temperature, 45% at average house temperature and 7% at rock bin return temperature. The temperature of the leakage collector air entering the house was assumed to be 3°C below the air temperature entering the storage. This estimate was necessary because the data system ignored the house duct temperature because the house fan was never on.

During the test period the house fan never did turn on, due probably to low storage temperatures. Thus, the only solar heat that entered the house was the estimated heat due to flow leaking around the internal baffle in the rock bin.

4.5 Data Base

The data acquisition system was installed on-site and operated from January 21, 1979 to March 18, 1979. Eighteen channels of data were recorded. Unfortunately, the second cassette tape containing data from February 12 to March 18 could not be read. It had evidently been exposed to a magnetic field of unknown origin.

The data base, thus, consists of 9180 data points taken during 510 hours or 21 days between January 21 and February 11, 1979. Each data point represents about 600 averaged readings, thus, there were about 5,500,000 individual readings.

5.0 HOURLY AND DAILY SUMMARY OF DATA

Figure 9 shows the equations used to format the summary data for this project. The hourly performance summary is shown in the tables in Appendix I. Table 1 is included in the main text and will be discussed as an example. Units of energy are mega joules, MJ, and temperatures are in degrees Celsius, ^{o}C. Table 1 shows the behavior of the system on a typical cold and sunny day. The sun strikes the collector at 9 AM but there are apparently some clouds until 10 AM. Between 11 AM and noon the collector fan turns on and stays on until shortly after 3 PM.

During this time the collector outputs approximately 72 MJ (76,000 BTU) of which 8 MJ (8,440 BTU) leaks into the house. The hourly heat load of the house is around 25 MJ/hr (26,400 BTU/hr) so the solar heat gain is very small. Note that the temperature of the shed which contains the rock bin increases $2^{o}C$/hr ($3.6^{o}F$/hr) while the collector fan is on. This is probably due to the hot air leak discussed previously.

The storage bin temperature, while the collectors are on, reflects basically the outlet air temperature of the solar collectors. This reaches a maximum of $40.5^{o}C$ ($105^{o}F$) which is about typical for this system over the cold test period. This performance is not remarkable since the collectors are sucking much of their inlet air out of the house which is only about $15^{o}C$ ($27^{o}F$) below their outlet temperature. When the fan turns off, the tempera-

ture at the top of the rock bin is 30°C (86°F) and drops to 25°C (77°F) by midnight. This temperature is too low to use in the house and the energy is dissipated during the night.

The attic temperature shows an increase of several degrees on some mornings around 7 AM. This may be due to a heat leak from the auxiliary heater. The bottom line in the table gives the sum of the hourly energy flows and the average temperatures.

6.0 OVERALL PERFORMANCE SUMMARY

Table 2 summarizes the hourly data given in Appendix I. The hourly heat quantities are summed over the entire test period and temperatures are averaged. The first part of Table 2 shows that 2% of the solar energy striking the collector surfaces was delivered to the house. This heat was entirely due to the leakage flow around the baffle in the rock storage. The house fan did not turn on during the test period so no stored solar heat was delivered to the house.

The energy inputs are compared to the calculated heat load in the second part of Table 2. The solar system is seen to contribute a negligible heat input, amounting to only 0.6% of the load. The electrical energy to run the fan used about 1/3 of this amount of energy and was dissipated in the attic.

The house temperature averaged 25°C (77°F) during the test period while the ambient temperature averaged -7.4°C (18.7°F). The temperature of the hot (top) end of the rock bin averaged 22.4°C (72°F) which is clearly below the house temperature and not usable.

7.0 COLLECTOR EFFICIENCY AND SHADING

The collector efficiency curves for this system are shown in Figure 10. The collector output as well as the inlet temperature were calculated using the same assumptions mentioned previously. Based on this approach, the efficiency falls well below the HUD reference for this type of collector. This seems plausible as the collector inlet temperature is high (since it draws heated air from the house) and since there are sizable leaks from the vent and the attic which dilute the solar-heated air.

Figure 11 shows the shading of the Salyer collector during the winter. There is some early morning shading due to trees along the street in front of the house and afternoon shading due to trees and mountains to the west.

The collector is exposed to the sun during the middle of the day when the radiation is most intense and usable. It can be concluded that these collectors have good exposure to the sun and that the shading would cause insignificant losses in efficiency.

8.0 HEAT LOAD CALCULATIONS

The calculations of heat load for the Salyer house are shown in Table 3. Part of the ceiling of this house is covered with an attic having vermiculite and fiberglass batts producing an insulation value of R-38. The roof over the kitchen and the back porch is a shed roof with R-11 insulation. Most of the windows have storm windows. The largest item in the heat load is the walls which are not insulated. The heat load factor used in the performance summary was reduced from the calculated value by 25%. This was done since the bedrooms and back porch are often closed off and are remote from the auxiliary heater in the living room. This produced a value of heat load which fit the experimental data better.

9.0 PROJECTED POTENTIAL PERFORMANCE

Figure 12 contains a plot of the output of the solar collector for a variety of values of daily total insolation. These values were taken from the summary data in Appendix I. This characteristic is combined with 1978-79 solar radiation data from the Hamilton High School and long-term degree day for Hamilton to produce the idealized annual performance projection shown in Table 4. This projection assumes that the present system is modified so that the heat delivered to the rock bin is actually used in the house. This analysis predicts an annual solar fraction of 22% and an overall collector efficiency of 13%.

The last column in Table 4 is auxiliary heat calculated from Mrs. Salyer's utility bills. Through November these values compare reasonably well with calculated heat loads using average degree days. During the winter, the fuel usage is over 60% higher than average.

Mrs. Salyer reports that last winter her fuel bills were a lot higher than normal. I believe she asked the utility company to replace her meter because she thought it was reading high. There are three factors which could contribute to these higher bills: (a) last winter was exceptionally cold, (b) there were utility rate increases, and (c) the solar system draws hot air from the house and deposits significant amounts of heat into storage where it

is lost. There is not enough data to determine the relative values of these factors at this time.

10.0 GRAPHICAL PRESENTATION OF DATA

Graphs of ten days of data are shown in Figures 13 and 14. The ambient temperatures were very low during the first seven days of this period. Six of these days were clear and the collectors operated for several hours each day. The daily peaks in the temperature of the shed containing the rock-bin heat storage are due to heat loss in this device. The attic temperature is approximately midway between house and ambient temperature. Since the attic-house interface is insulated to R-38, this high attic temperature indicates that hot air from the house is entering the attic. The house temperature shows a small decrease each day when the solar collector fan turns on. This behavior is consistent with the flow measurements depicted in Figure 7 which shows that the collector fan pumps air from the house.

11.0 CONCLUSIONS

This solar system did not produce significant heat during the cold test period. If no modifications are made, the system should be turned off during cold weather. Modifications which appear advisable to increase the energy efficiency of this house are listed below in the order of importance:

(1) Add motorized damper to house loop and remove baffle from heat storage bin.

(2) Seal air leaks.

(3) Lower the house temperature.

(4) Close summer vent securely.

(5) Increase insulation of heat storage bin.

(6) Seal off ceiling vents and add floor-level cold air return to rock bin.

(7) Adjust and use the differential thermostat and check operation of other controls.

(8) Equalize flow in collectors.

TABLE 1

EXAMPLE OF HOURLY PERFORMANCE DATA

DAILY PERFORMANCE SUMMARY FOR SALYER HOUSE (ID='I')

REC#	MO	DAY	HR	SOLAR INSO MJ	COLL OUTPT MJ	SOLAR HOUSE MJ	STORE HOUSE MJ	ELECT POWER MJ	HOUSE LOAD MJ	DEG HRS C	KW HR	STORE TEMP C	SHED TEMP C	ATTIC TEMP C	HOUSE TEMP C	AMBNT TEMP C	SOLAR INSO KWSM*10	
14	1	22	1	.0	.0	.0	.0	2.7	24.1	27.4	.8	11.9	5.5	1.5	24.0	-3.5	.0	
15	1	22	2	.0	.0	.0	.0	3.0	24.2	27.6	.8	12.0	5.2	1.7	23.1	-4.5	.0	
16	1	22	3	.0	.0	.0	.0	2.8	24.2	27.6	.8	12.1	4.9	1.6	22.4	-5.1	.0	
17	1	22	4	.0	.0	.0	.0	2.0	24.5	27.9	.6	12.2	4.6	1.1	21.8	-6.1	.0	
18	1	22	5	.0	.0	.0	.0	2.9	26.8	30.5	.8	12.4	4.1	1.6	21.2	-9.3	.0	
19	1	22	6	.0	.0	.0	.0	2.3	26.7	30.4	.6	12.5	3.6	1.3	20.8	-9.6	.0	
20	1	22	7	.0	.0	.0	.0	6.4	26.5	30.3	1.8	12.5	3.4	3.6	22.0	-8.2	.0	
21	1	22	8	.0	.0	.0	.0	8.7	28.3	32.2	2.4	12.3	3.3	4.9	24.9	-7.3	.0	
22	1	22	9	1.0	.0	.0	.0	2.9	28.0	31.9	.8	11.9	3.1	1.6	25.3	-6.6	.1	
23	1	22	10	6.8	.0	.0	.0	2.3	26.9	30.7	.6	11.6	2.9	1.3	25.3	-5.4	.7	
24	1	22	11	55.5	.0	.0	.0	3.5	25.7	29.3	1.0	11.2	3.0	2.0	26.0	-3.3	5.4	
25	1	22	12	83.7	9.6	.9	.0	3.2	25.2	28.7	.9	21.7	4.4	1.8	26.3	-2.4	8.2	
26	1	22	13	89.5	21.9	2.6	.0	5.3	23.6	26.9	1.5	37.9	7.0	3.0	26.0	-.9	8.7	
27	1	22	14	88.6	23.0	3.0	.0	5.2	23.7	27.0	1.4	40.5	9.1	2.9	26.9	-.1	8.6	
28	1	22	15	64.2	17.5	1.7	.0	4.9	22.2	25.3	1.4	34.8	11.1	2.8	25.3	-.0	6.3	
29	1	22	16	25.3	.1	-.0	.0	2.8	21.6	24.6	.8	30.0	10.9	1.6	24.4	-.2	2.5	
30	1	22	17	9.7	.0	.0	.0	3.2	22.5	25.6	.9	28.7	9.7	1.8	24.0	-1.6	1.0	
31	1	22	18	1.0	.0	.0	.0	3.8	24.4	27.8	1.1	27.7	8.1	2.1	24.4	-3.4	.1	
32	1	22	19	.0	.0	.0	.0	5.5	26.2	29.9	1.5	27.1	7.4	3.1	25.3	-4.5	.0	
33	1	22	20	.0	.0	.0	.0	5.5	25.7	29.3	1.5	26.6	6.4	3.1	25.2	-4.1	.0	
34	1	22	21	.0	.0	.0	.0	5.9	27.3	31.1	1.6	26.1	6.2	3.3	26.4	-4.7	.0	
35	1	22	22	.0	.0	.0	.0	6.5	28.2	32.1	1.8	25.8	5.8	3.7	26.9	-5.2	.0	
36	1	22	23	.0	.0	.0	.0	8.0	28.8	32.8	2.2	25.6	5.5	4.5	27.0	-5.8	.0	
37	1	23	0	.0	.0	.0	.0	2.7	27.1	30.9	.8	25.4	4.9	1.5	24.0	-7.0	.0	
DAY	1	22	24	425.3	72.2	8.1	.0	102.1	612.3	697.7	28.4	21.3	5.8	2.4	24.5	-4.5	1.7	SUM-AVG

TABLE 2

OVERALL PERFORMANCE SUMMARY OF SALYER HOUSE DURING MONITORING PERIOD

	[3]MJ	[4]MBTU	%
Total Insolation	6750	7.1	100
Collector Output	986	1	15
Solar to House	96	0.1	2
Solar Storage to House	0	0	0
[1]House Heat Load	(14142)	14.9	100
[2]Solar Heat	96	0.1	6
Electric Input	3315	3.5	23
[1]Auxiliary	(10731)	11.3	76

Average Temperatures	°C	°F
House	25	77
Ambient	- 7.4	18.7
Rock Bin Storage (Top)	22.4	72

[1] Calculated, ±20%

[2] Note: The fan absorbed about 35 MJ of electricity during the test period.

[3] Mega Joules

[4] Millions of BTU's

TABLE 3

CALCULATED HEAT LOAD FACTOR FOR SALYER HOUSE

	R	U (Btu/hr ft^2 ^{o}F)	AREA (sq. ft.)	U X A
Roof				
Shed	11	.091	360	33
Attic	38	.026	754	20
Walls				
Nominal	4	.25	840	210
Rock Bin	24	.041	102	4
Floor	[1]8	.12	1114	133
Windows				
Single	.9	1.13	24	27
Storm	1.8	.55	186	103
Infiltration:	10,000 X 0.5 X 0.018			90
			Total Heat Load	619 Btu/hr^{o}F or 1.17 MJ/hr^{o}C

[1] Effective R, over crawl space

[2] Assuming $\frac{1}{2}$ air change per hour

TABLE 4

[1]PROJECTED POTENTIAL YEARLY PERFORMANCE

Month	Degree Days, °C	Insol @ 60°	Tilt Factor	Insol @ 45°	Solar Avail MJ/day	[1]Solar Heat MJ/day	Heat Load MJ/day	[2]Aux Heat
July	15	4.7	1.11	5.21	533	110 (11)	11	
August	36	4.33	1.07	4.63	474	90 (25)	25	100
Sept.	148	3.55	1.02	3.62	371	60	104	119
Oct.	318	5.14	.99	5.08	521	106	223	182
Nov.	503	2.18	.95	2.07	212	12	353	387
Dec.	638	2.37	.94	2.23	228	20	448	(700)
Jan.	692	2.88	.95	2.73	280	31	486	746
Feb.	525	2.37	.97	2.30	235	20	369	543
March	496	4.11	1.02	4.19	430	75	348	
April	321	3.81	1.07	4.08	418	72	225	
May	201	4.34	1.12	4.86	498	98	141	
June	95	4.35	1.13	4.91	504	100 (67)	67	
TOTALS	3701				4704	594	2800	

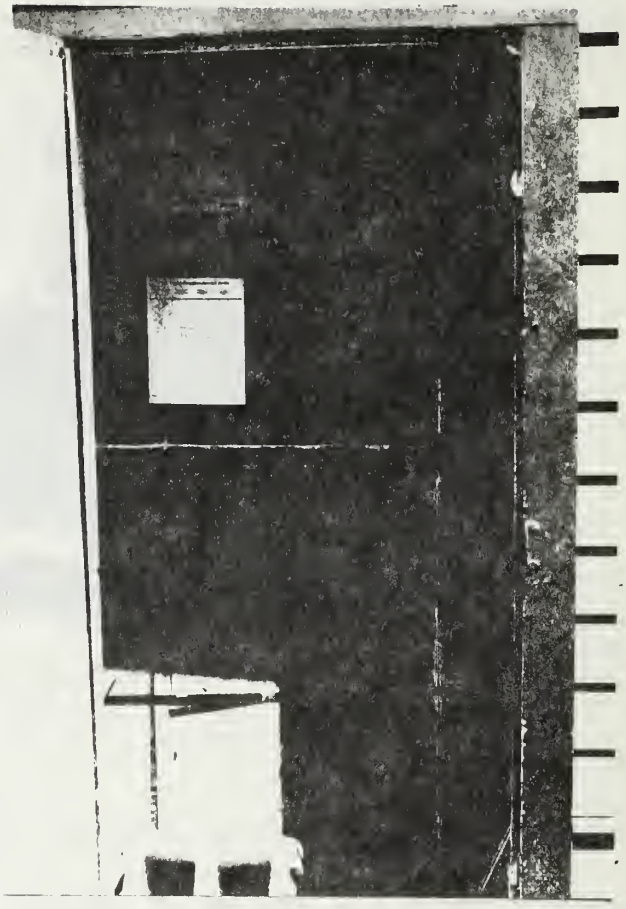
[1] This assumes system is modified to increase efficiency.
[2] Based on utility bills.

(a) East side of Salyer house

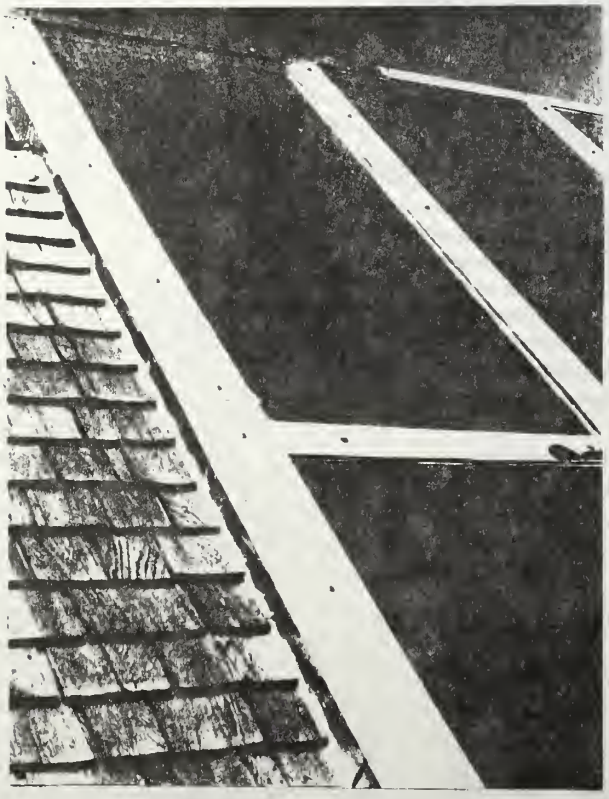
(b) North side of Salyer roof showing collectors extending past ridge.

Figure 1: Salyer house photographs

(a) Solar collectors, vent and rock bin enclosure



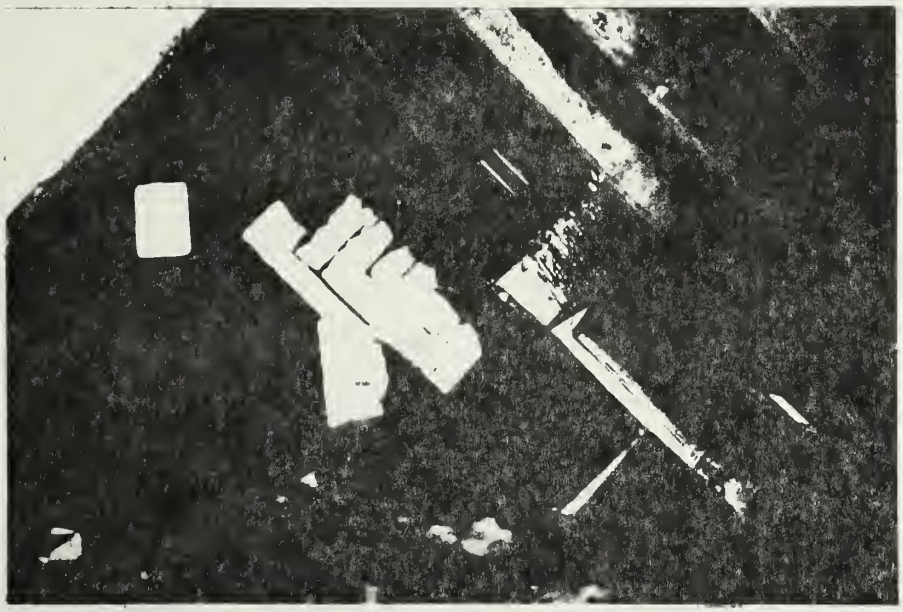
(b) Plywood rock bin inside attached enclosure



(c) Close up of collectors

(d) SE corner of house

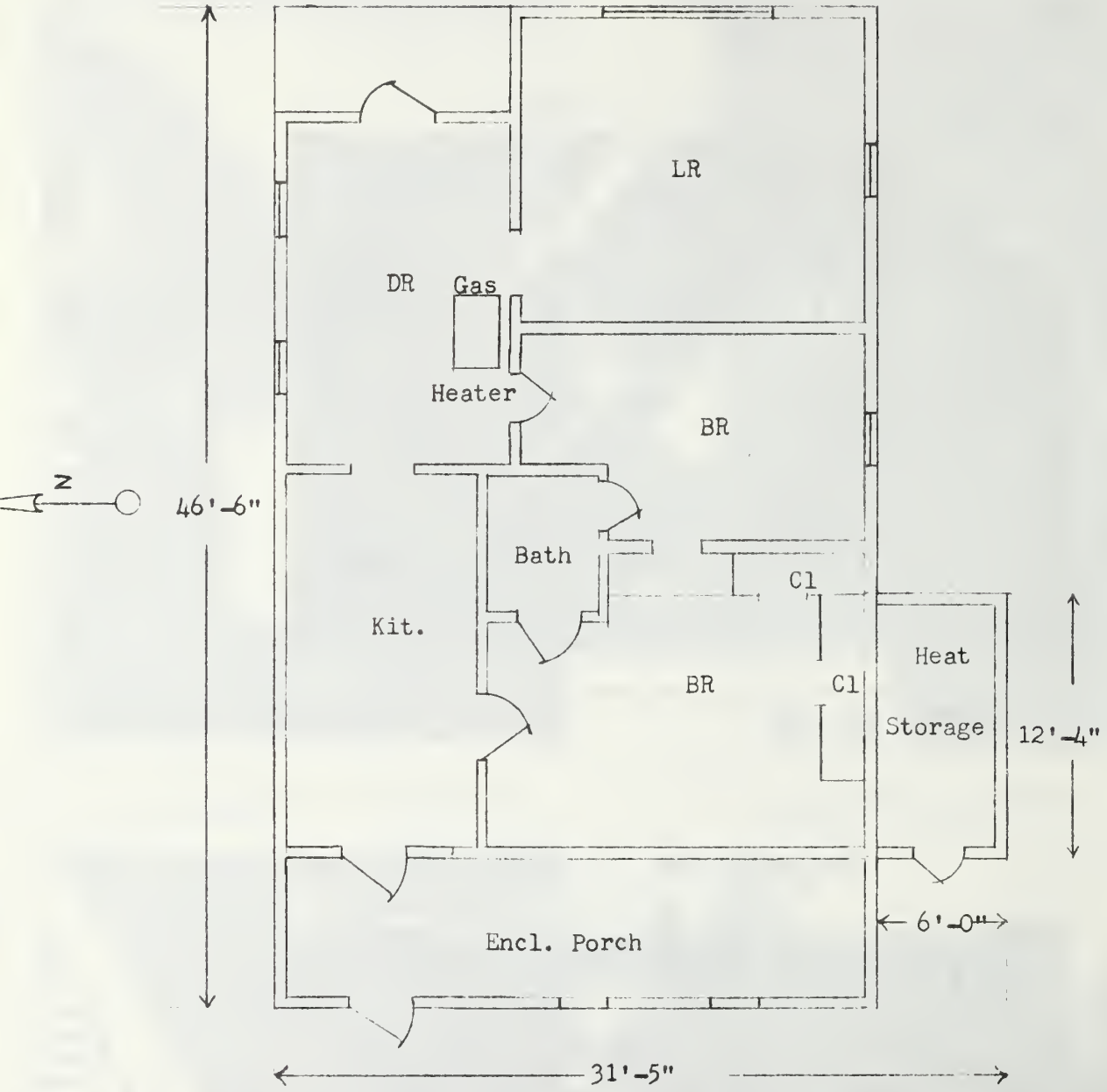
Figure 2. Salvan house photographs



(a) Collector supply and return ducting

(b) Collector fan, ducting and wiring

Figure 3: Attic of Salyer house



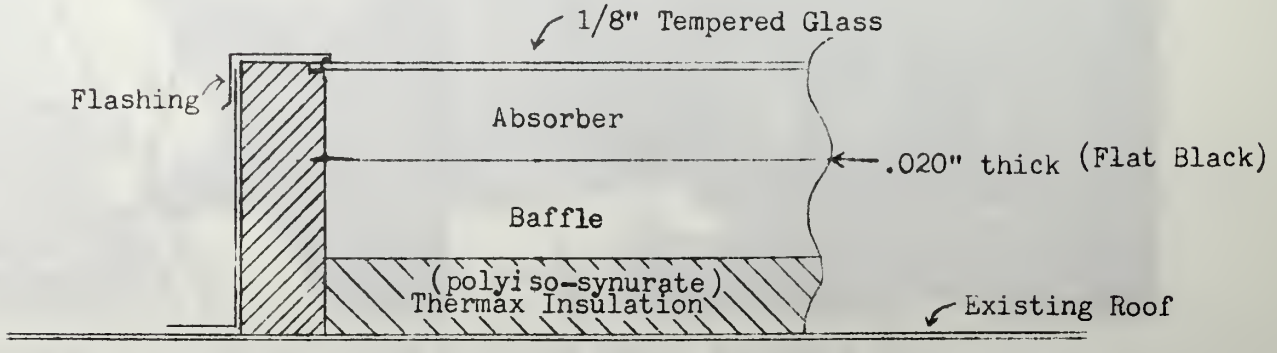


Figure 4: Floor plan of house and schematic of collector construction

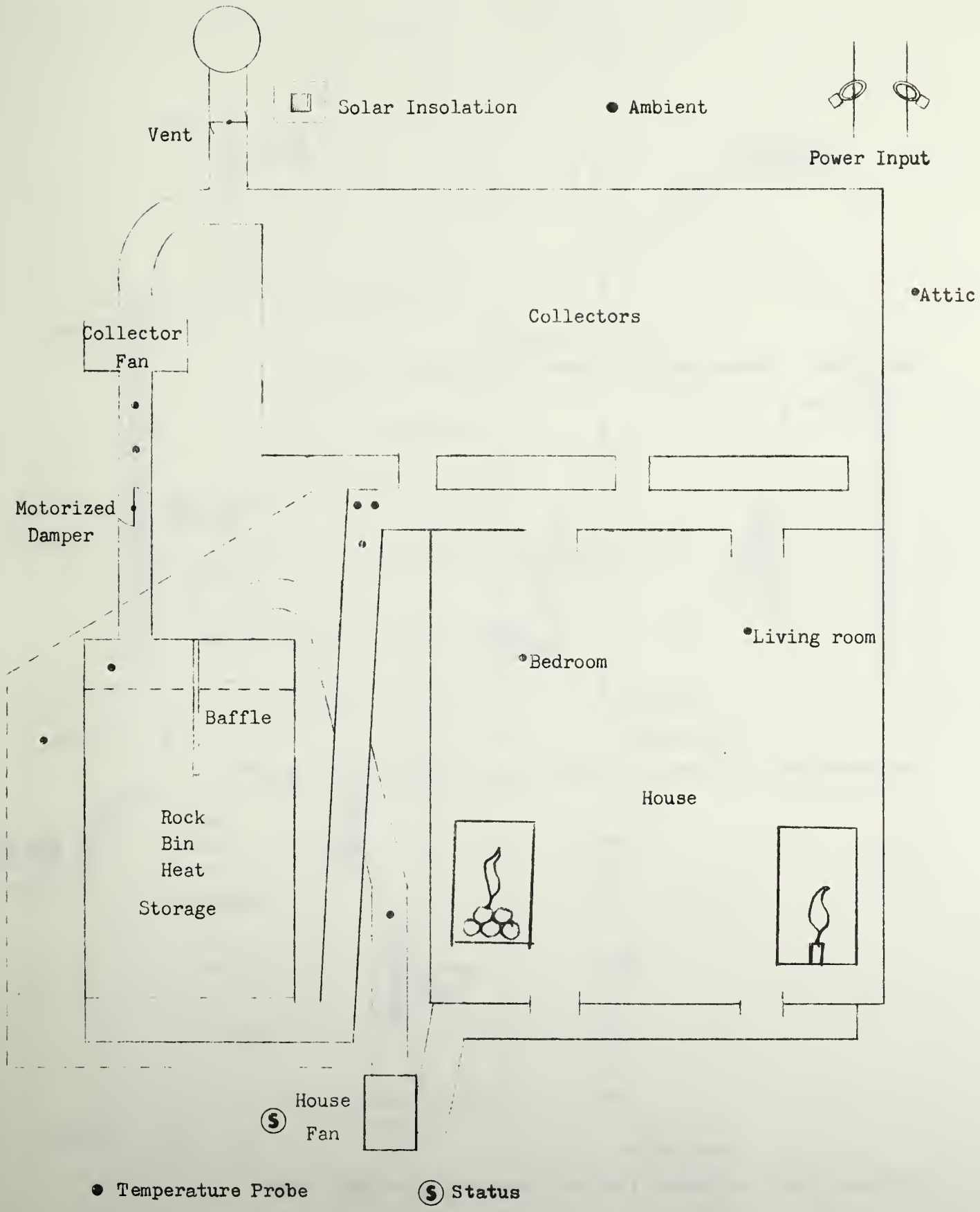
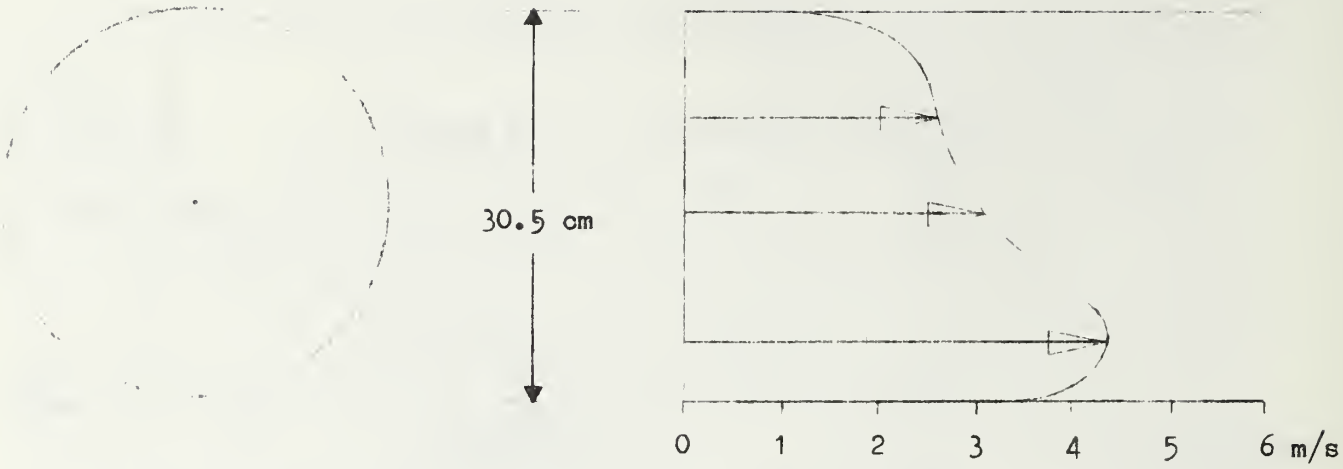
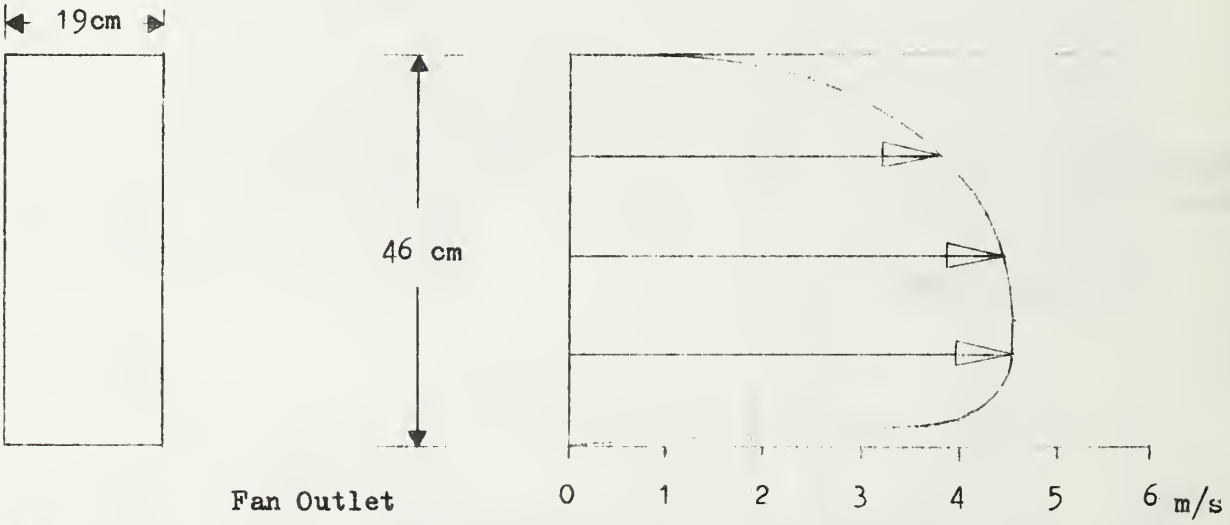


Figure 5: Schematic of solar heating system showing instrumentation arrangement.

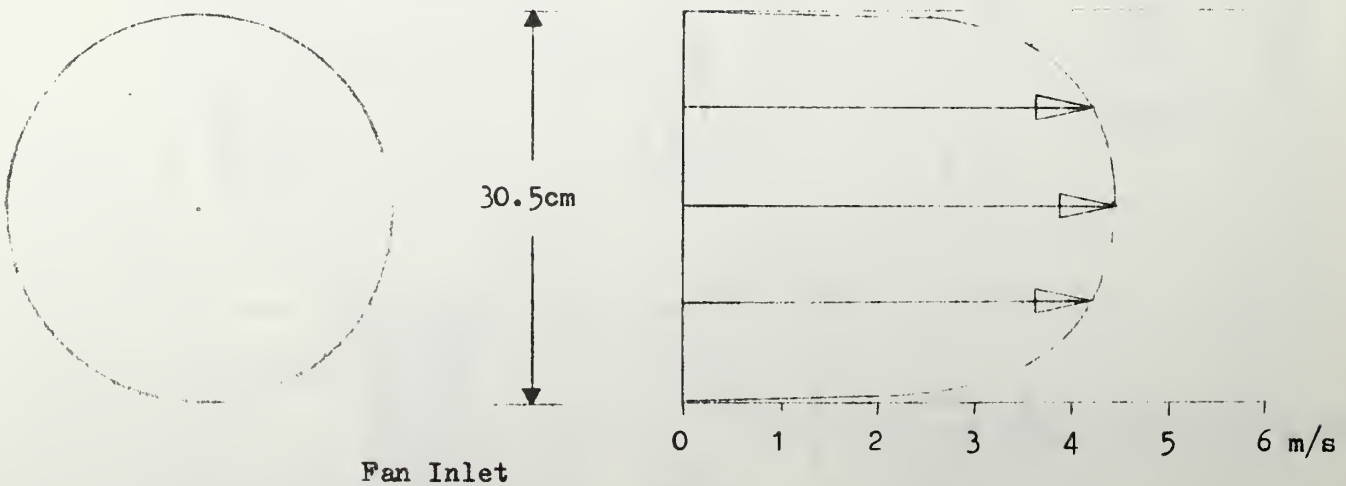


House Duct, House Fan On : Flow= 13.54 m^3/min, T=18°



Fan Outlet

Collector Out, Collector Fan On : Flow = 16.35 m^3/min, T=28°C



Fan Inlet

Collector Out, Collector Fan On : Flow= 15.24 m^3/min, T=28°

Figure 6: Flow profiles resulting from scanning the ducts using a hot wire anemometer.

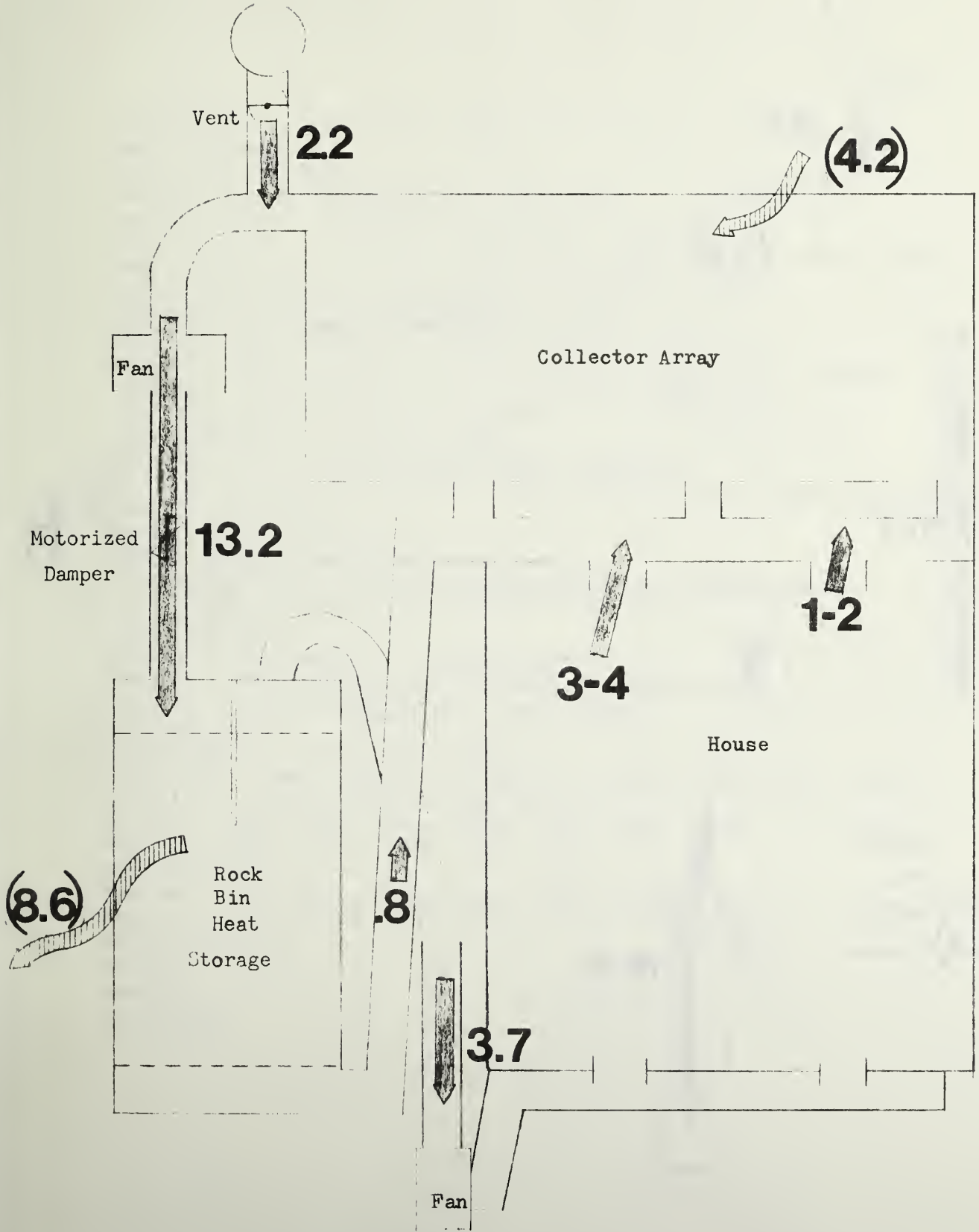


Figure 7: Flow Balance and Leaks; Collector fan - on, House fan - off. Flow in m^3/min.

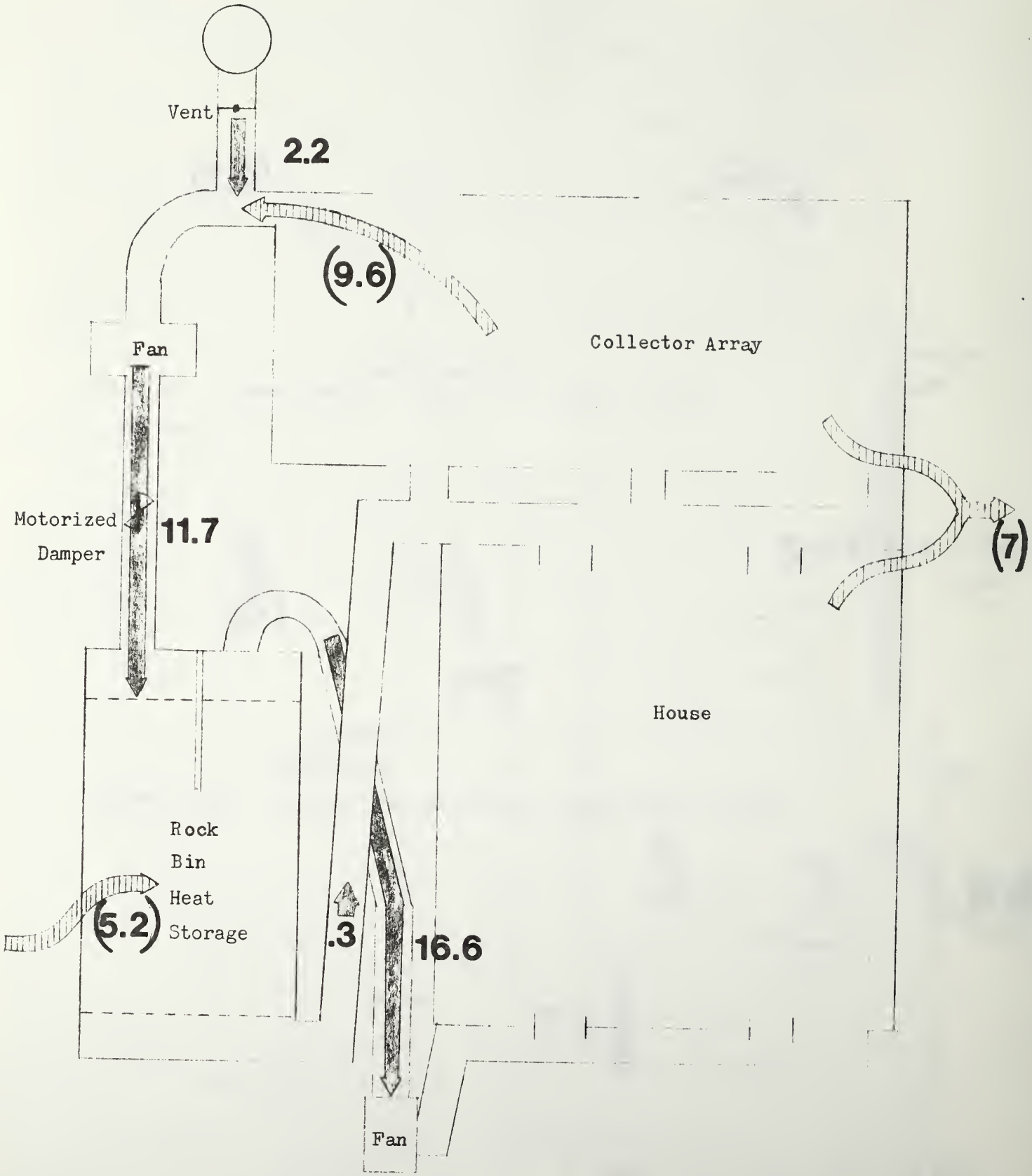


Figure 8: Flow Balance and Leaks; Collector fan is on and House fan is on. Flow in cubic meters/minute.

```
3000REM SUBR *** COMPUTE HOURLY SUMS ***********************************
3005 !"-- SUMMING"
3010 N0=N0+1\REM #HRS
3012 REM  ALL THE FOLLOWING ARE IN MEGA JOULES
3015 S(1)=(D(1)-.01)*.95*28.46*3.6\REM SOLAR INPUT
3018 T1=.16*D(7) + .32*D(10) + .45*(D(8)+D( 9))/2 + .07*D(11)\REM AVG TIN
3020 S(2)=13.2*.06*1.2*1.01*((D(15)/(D(4)+.0001))-T1)*D(4)
3025 T2=(D(8)+3*D(9))/4 \ REM AVERAGE HOUSE TEMPERATURE
3030 S(3)=3.7*.06*1.2*1.01*((D(15)/(D(4)+.0001))-3-T2) *D(4)
3035 REM ABOVE IS SOLAR HEAT TO HOUSE, ASSUMES 3C TEMP DROP
3040 S(4)=D(5)*16.6*.06*1.2*1*(D( 9)-D(13))\REM STORAGE HEAT TO HOUSE
3050 S(5)=(D(2)+D(3))*3.6*.494  \REM ELECTRICAL POWER INPUT
3060 S(6)=1.17*(T2-D(7))*.75 \ REM HOUSE HEAT LOAD, CORRECTED X.75
3062 S(7)=T2-D(7) \ REM DEGREE HOURS
3065 S(8)=(D(2)+D(3))*.494 \REM KW INPUT, CORRECTED
3070 S(9)=D(12)\S(10)=D(16)\S(11)=D(10)\S(12)=T2\S(13)=D(7)\REM TEMPERATURES
3080 S(11)=D(2)+D(3)
3085 S(14)=(D(1)-.01)*.95*10
3130 !#1,%3I,R,%4I,M0,%3I,D0,%5I,H0,TAB(15),
3140 FOR I=1 TO 14\T(I)=T(I)+S(I)\REM SUM FOR DAY, PRINT HR DATA
3150 !#1,%7F1,S(I),\NEXT\!#1
3160 RETURN\!#1
3200REM *** CALC AVERAGES & FINAL QUANTITIES
3210 FOR I= 9TO 14\ REM AVERAGE TEMPERATURES (NOTE HEATS NOT INCL.,)
3220 T(I)=T(I)/N0\REM DAILY AVGS = SUM / NR HRS
3230 NEXT\RETURN
3400REM SUBR *** PRINT REPORT HEADING
3405 !#1\!#1"  DAILY PERFORMANCE SUMMARY FOR  SALYER  HOUSE (ID=",R$,")"
3410 !#1\!#1,"REC# MO DAY  HR ",TAB(16),
3420 !#1," SOLAR   COLL  SOLAR  STORE  ELECT  HOUSE    DEG     KW  STORE ",
3430 !#1,"  SHED  ATTIC  HOUSE  AMBNT  SOLAR"
3440 !#1,TAB(16),
3450 !#1," INSO  OUTPT  HOUSE  HOUSE  POWER   LOAD    HRS     HR   TEMP ",
3460 !#1, "  TEMP   TEMP   TEMP   TEMP   INSO"
3464 !#1,TAB(16),
3465 !#1,"    MJ     MJ     MJ     MJ     MJ     MJ      C             C ",
3466 !#1, "     C      C      C      C   KWSM*10"
3495 RETURN
```

Figure 9: Computer equations for heat quantities

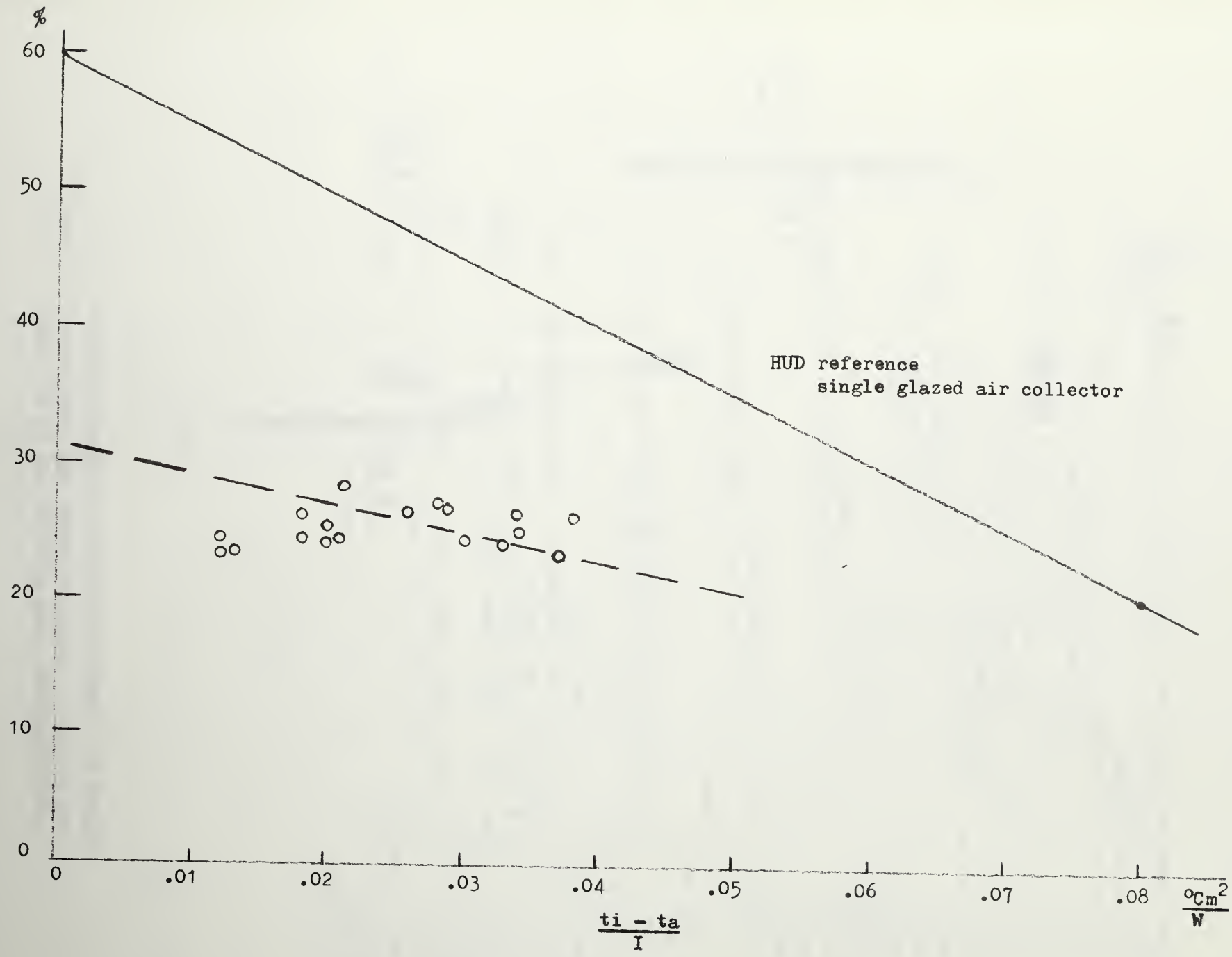


Figure 10: Collector efficiency curves

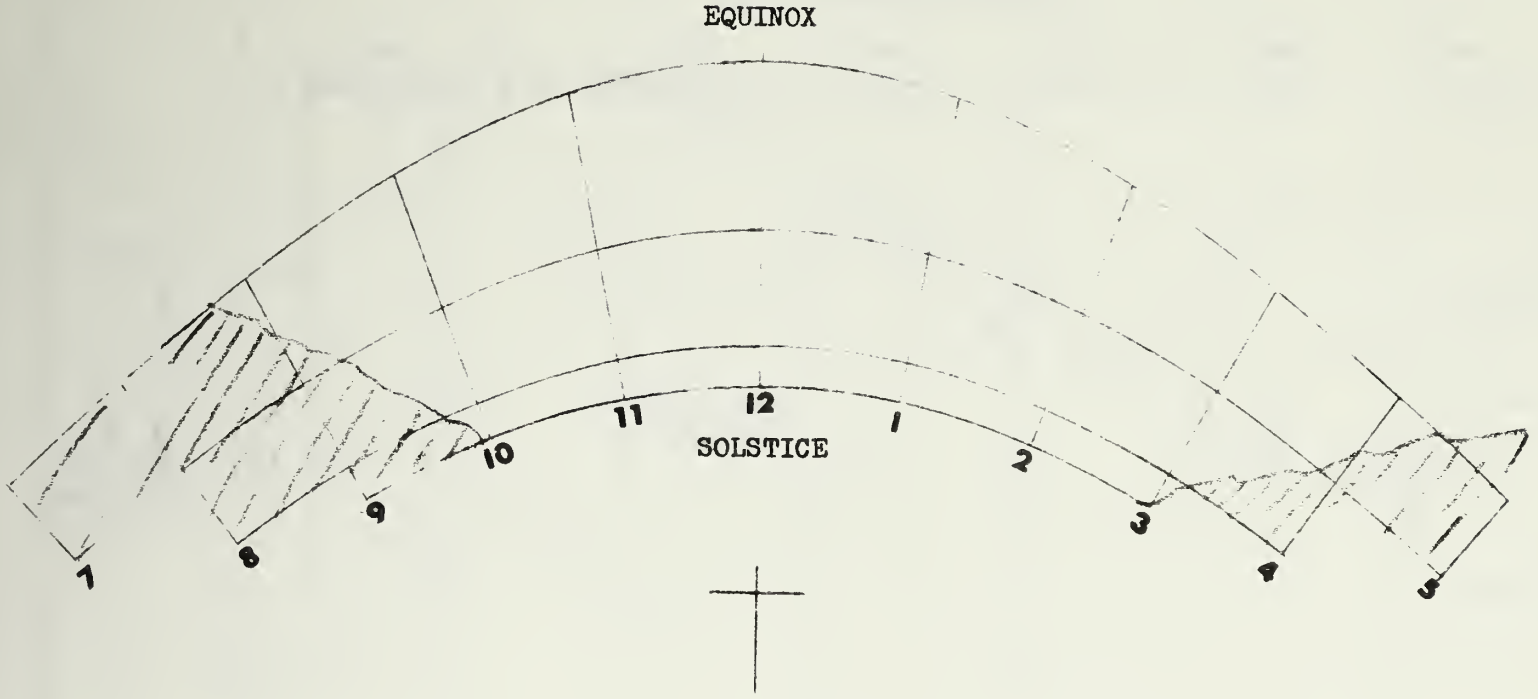


Figure 11: Winter shading of Salyer collector

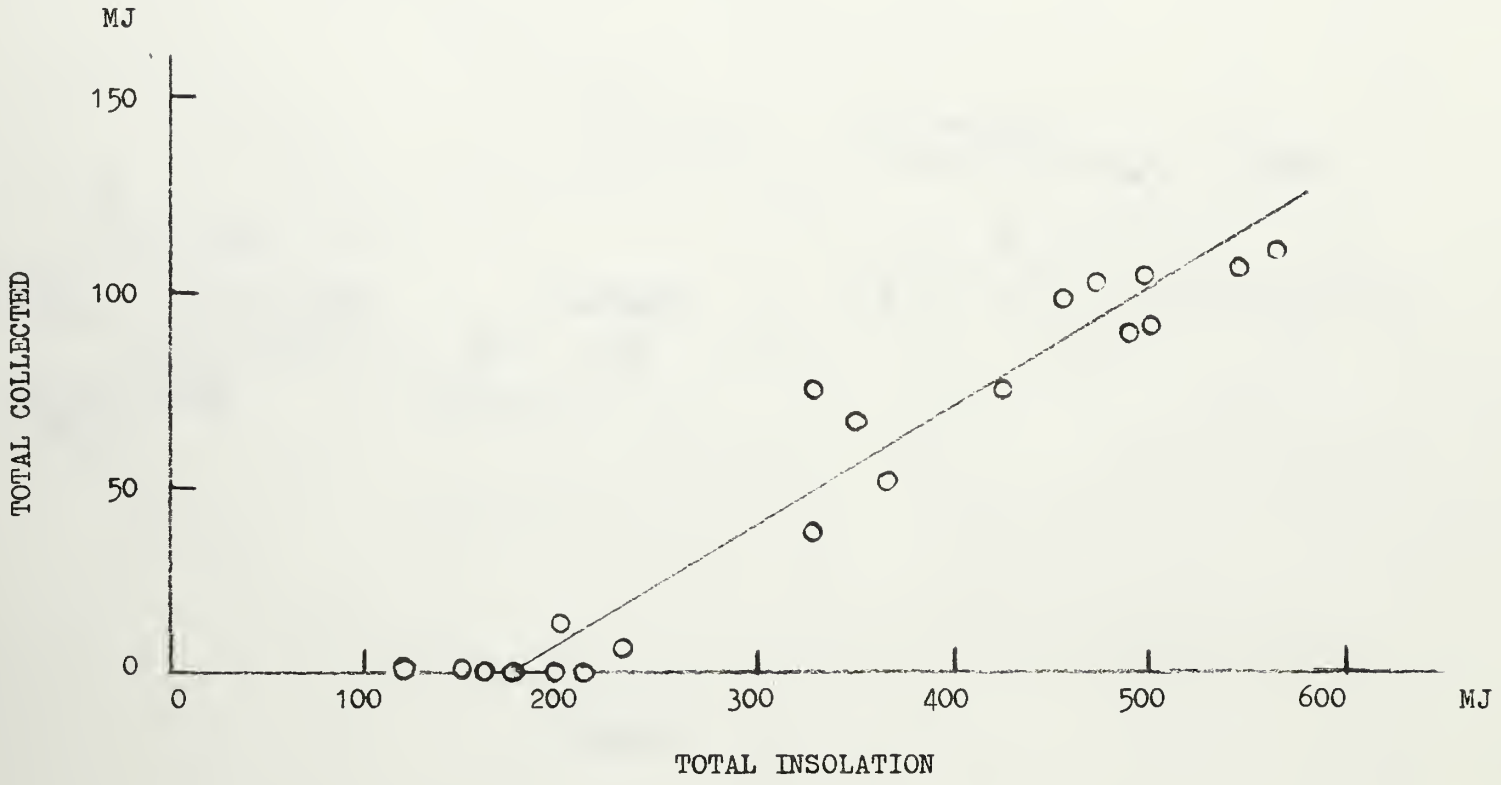


Figure 12: Daily average collector performance

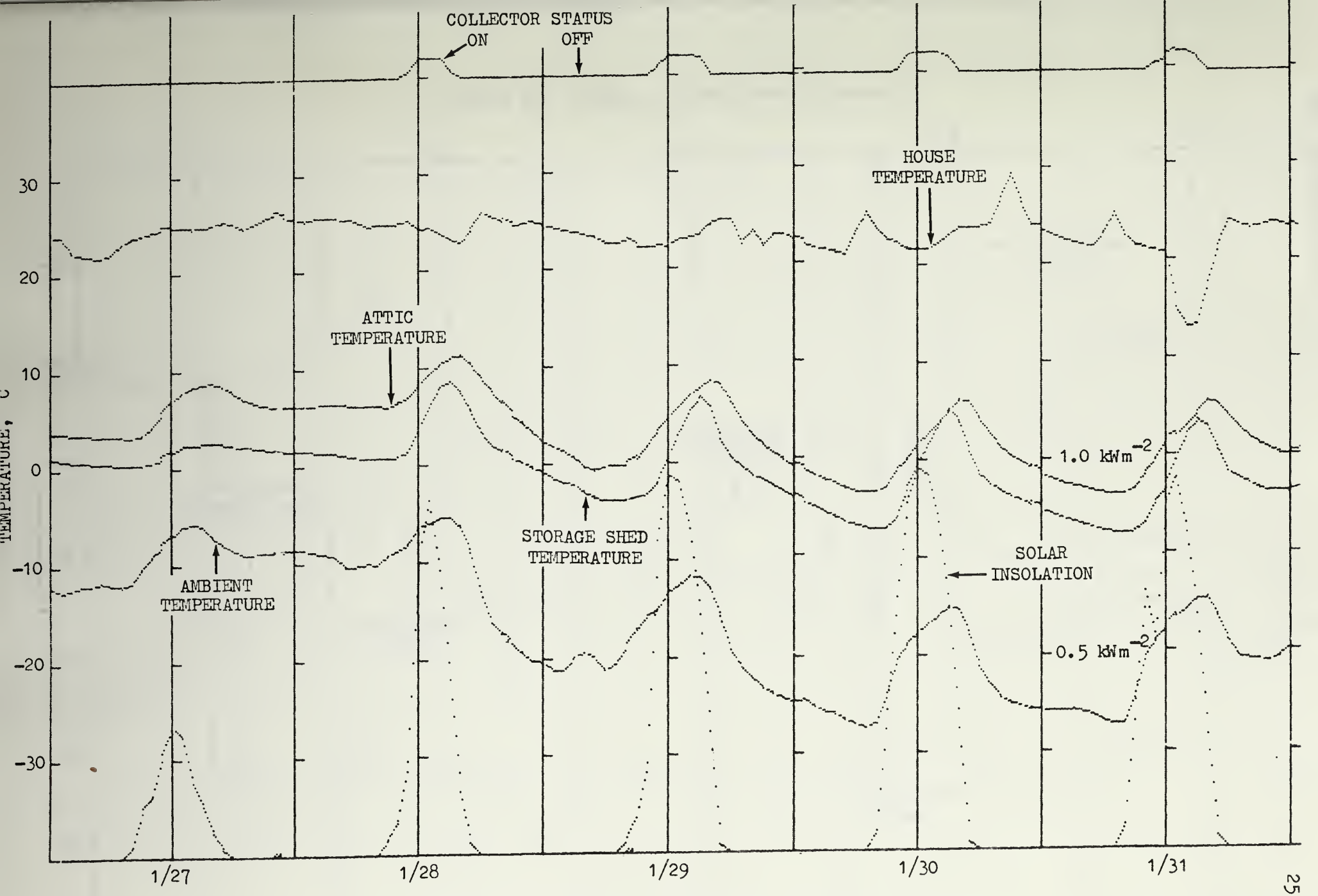


Figure 13: Graph of 5 Days Data in January

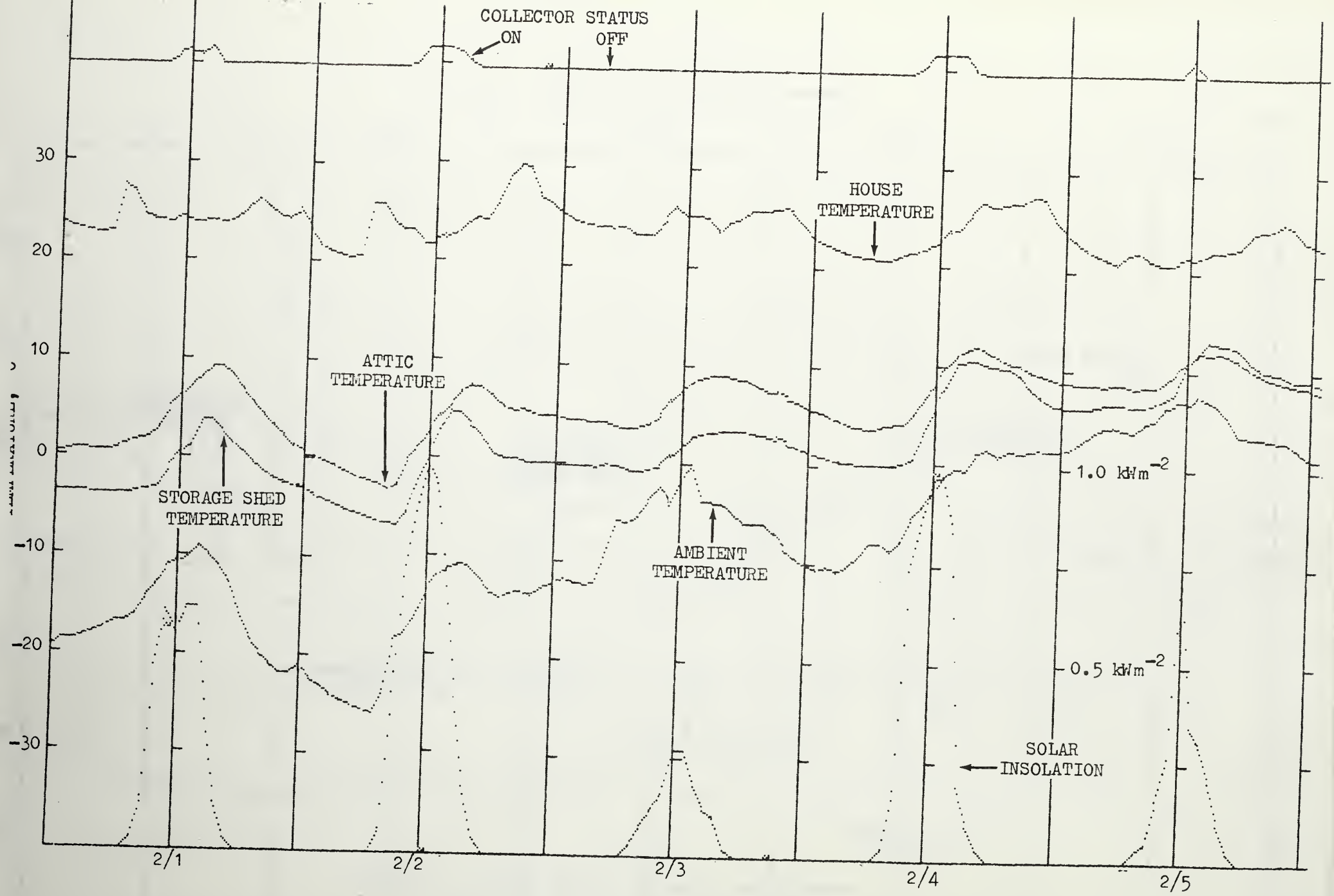


Figure 14: Graph of 5 Days Data in February

APPENDIX I

HOURLY PERFORMANCE DATA FOR SALYER HOUSE BETWEEN 1/23 AND 2/10

TABLE 1

DAILY PERFORMANCE SUMMARY FOR SALYER HOUSE (ID='I')

REC#	MO	DAY	HR	SOLAR INSO MJ	COLL OUTPT MJ	SOLAR HOUSE MJ	STORE HOUSE MJ	ELECT POWER MJ	HOUSE LOAD MJ	DEG HRS C	KW HR	STORE TEMP C	SHED TEMP C	ATTIC TEMP C	HOUSE TEMP C	AMBNT TEMP C	SOLAR INSO KWSM*10	
38	1	23	1	.0	.0	.0	.0	1.9	25.7	29.3	.5	25.2	4.7	1.1	22.8	-6.6	.0	
39	1	23	2	.0	.0	.0	.0	3.0	26.5	30.2	.8	25.1	4.3	1.7	22.0	-8.1	.0	
40	1	23	3	.0	.0	.0	.0	2.3	27.1	30.9	.6	24.9	4.0	1.3	21.5	-9.4	.0	
41	1	23	4	.0	.0	.0	.0	2.0	27.7	31.6	.5	24.6	3.3	1.1	21.0	-10.6	.0	
42	1	23	5	.0	.0	.0	.0	2.8	26.6	30.4	.8	24.4	3.0	1.6	20.6	-9.8	.0	
43	1	23	6	.0	.0	.0	.0	6.1	27.3	31.1	1.7	24.1	2.2	3.4	21.0	-10.1	.0	
44	1	23	7	.0	.0	.0	.0	7.5	30.2	34.4	2.1	23.8	1.5	4.2	24.2	-10.3	.0	
45	1	23	8	.0	.0	.0	.0	8.1	30.5	34.8	2.2	23.4	1.1	4.5	24.4	-10.4	.0	
46	1	23	9	2.9	.0	.0	.0	3.0	30.3	34.5	.8	23.0	-.2	1.7	24.6	-9.9	.3	
47	1	23	10	27.3	.0	.0	.0	2.2	28.9	32.9	.6	22.6	-.4	1.2	24.2	-8.7	2.7	
48	1	23	11	65.2	3.7	.3	.0	2.5	27.8	31.6	.7	23.9	.1	1.4	24.7	-7.0	6.4	
49	1	23	12	85.7	19.5	1.7	.0	3.5	25.6	29.1	1.0	33.5	6.8	2.0	24.8	-4.3	8.4	
50	1	23	13	90.5	22.4	2.4	.0	5.8	27.5	31.4	1.6	37.2	7.0	3.2	25.6	-5.8	8.8	
51	1	23	14	72.0	18.7	1.5	.0	3.9	27.6	31.4	1.1	34.5	8.3	2.2	25.8	-5.6	7.0	
52	1	23	15	85.7	21.7	2.5	.0	3.8	25.6	29.2	1.1	38.0	9.8	2.1	25.9	-3.3	8.4	
53	1	23	16	55.5	14.6	1.1	.0	5.0	25.5	29.1	1.4	32.8	11.1	2.8	25.5	-3.6	5.4	
54	1	23	17	22.4	.0	.0	.0	9.3	28.1	32.1	2.6	29.4	10.4	5.2	27.3	-4.8	2.2	
55	1	23	18	1.0	.0	.0	.0	4.9	31.0	35.4	1.4	28.0	8.3	2.8	28.0	-7.4	.1	
56	1	23	19	.0	.0	.0	.0	16.2	32.9	37.5	4.5	26.9	6.4	9.1	27.7	-9.8	.0	
57	1	23	20	.0	.0	.0	.0	7.0	34.6	39.4	2.0	26.1	4.4	4.0	27.3	-12.1	.0	
58	1	23	21	.0	.0	.0	.0	7.3	34.7	39.6	2.0	25.6	3.8	4.1	26.4	-13.2	.0	
59	1	23	22	.0	.0	.0	.0	9.5	33.8	38.5	2.6	25.2	3.1	5.4	24.9	-13.6	.0	
60	1	23	23	.0	.0	.0	.0	7.8	35.6	40.5	2.2	24.9	2.7	4.4	26.7	-13.9	.0	
61	1	24	0	.0	.0	.0	.0	1.6	31.8	36.2	.4	24.7	2.5	.9	23.2	-13.1	.0	
DAY	1	23	24	508.1	100.5	9.5	.0	127.0	702.9	801.1	35.3	27.2	4.5	3.0	24.6	-8.8	2.1	SUM-AVG

THERMAL PERFORMANCE
OF THE MATTSON SOLAR HOUSE

by

Charless W. Fowlkes

FOWLKES ENGINEERING
31 Gardner Park Drive
Bozeman, MT 59715

for

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
RENEWABLE ALTERNATIVE ENERGY SOURCES PROGRAM
John Orndorff, Bureau Chief

NOTICE

This report was prepared as an account of work sponsored by the Energy Division of the Montana Department of Natural Resources and Conservation through the Alternative Renewable Energy Sources Program. Neither the State of Montana, nor the Department, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

ABSTRACT

This residence is owned by the George Mattson family and is located about three miles south of Bozeman, Montana. The active air solar system uses 600 ft^2 of collectors, a single fan and a rock bin for heat storage. The performance of the house was monitored during the late winter and spring of 1979. This is a new house and the Mattsons moved into it in mid-April 1979.

The monitoring data showed that this system had several operational problems including air leaks, damper malfunctions and erratic control behavior. The blower motor was replaced at one point. The owner and contractor are in the process of making major changes in the system in hopes of improving its performance. The low performance of this project reflects the net effect of these problems.

During the monitoring period, the collectors delivered a total of 15% of the available solar insolation to the house. Of the solar heat sent to storage, 80% was lost. The annual solar fraction was estimated to be a maximum of 30%. If the system problems can be fixed, the solar efficiency should be about twice its current value.

NOTE ON UNITS

The data is presented in metric units. These units are in accord with the recommendations of the International Solar Energy Society as well as most current technical journals. The overall summaries and numbers in the test have been given in dual units. The heat load calculations are presented in conventional units.

Most readers are familiar with the Celsius or Centigrade temperature scale and are also familiar with energy units of kilowatt hours. The only other metric unit which occurs frequently in this report is the Joule (J), the metric unit of energy which replaces the Btu (a Btu is equal to 1,055 Joules). The mega joule (MJ) is equal to 10^6J (100,000 Btu/hr = 105 MJ/hr).

Other abbreviations used in this report include: m = meters; m^2 = square meters; l = liters; h = hours; gph = gallons per hour; and MBtu = millions of Btu's.

TABLE OF CONTENTS

1.0 Acknowledgment 1
2.0 Introduction 1
3.0 Description of House 1
4.0 The Solar System 2
5.0 Performance Monitoring
5.1 Flow Measurements 2
5.2 Data Analysis Flow Approximations 3
5.3 Collector Efficiency Curves 4
5.4 Hourly Performance Summary 4
6.0 Overall Performance Summary 5
7.0 Projected Annual Performance 6
8.0 Graphical Presentation of Data 6
9.0 Conclusions 7

TABLES

Table 1 - Mattson House Heat Load 8
Table 2 - Key to Items in Data Tables 9
Table 3 - Sample Hourly Performance Summary 10
Table 4 - Daily Performance Summary 11
Table 5 - Overall Summary for 25 Days 12
Table 6 - Solar Insolation Comparison 12
Table 7 - Projected Yearly Performance Summary 13

FIGURES

Figure 1 - Mattson Solar House 14
Figure 2 - Mechanical Equipment Room 15
Figure 3 - Floor Plan of Mattson House 16
Figure 4 - Section, Mattson House 17
Figure 5 - Shading Diagram, Mattson House 18
Figure 6 - System Schematic with Transducer Layout and Control Matrix 19
Figure 7 - Flow To and From Collectors 20
Figure 8 - Flow To and From House 21
Figure 9 - Schematic With Flow Rates in Cubic Meters/Minute 22
Figure 10 - Collector Efficiency Curves 23
Figure 11 - Computer Heat Balance Equations 24
Figure 12 - Overall Collector Performance Curve 25
Figure 13 - Graph of 5 Days Data in May 26
Figure 14 - Graph of 5 Days Data in May 27

APPENDICES

Appendix I - Tables of Hourly Data for Mattson House
Appendix II - Passive Operation of Solar Collectors, Mattson House

1.0 ACKNOWLEDGMENT

The cooperation of Mr. Mattson and his family was necessary for the successful execution of this monitoring effort. Mr. Mattson supplied us with a key to the house which allowed us easy access for installing and maintaining the data acquisition system. We were allowed to drill numerous holes in the ductwork for measuring flow and temperature and the Mattson family did not object to working around the large number of transducer wires required for this project. Mr. Mattson spent several hours with us during the installation of the system and helped interpret and verify some of the data. This cooperation and enthusiasm is gratefully acknowledged.

A preliminary draft of this report was read by Kitty Kvinge, Jim Iversen and Dana Gunderson. Their comments and suggestions are reflected in this final version. Their contributions and support of this project are gratefully acknowledged.

2.0 INTRODUCTION

The Mattson residence is located about three miles south of Bozeman. The house and the solar system were designed by Mr. Mattson who is a registered architect. The Mattson family did a large portion of the construction of this house which has spanned 1977 to the present. The house has been occupied since mid-April, 1979.

3.0 DESCRIPTION OF HOUSE

Figures 1 and 2 show photographs of the Mattson solar house and a floor plan and elevation view are shown in Figures 3 and 4. The house is well insulated and is oriented to conserve energy. Solar heat is supplied to the house by an active air system combined with passive clerestory windows. An internal masonry wall receives radiation from the winter sun through the clerestory windows. A natural gas furnace and a wood stove supply auxiliary heating. The calculated heat load for this house is shown in Table 1.

A shading diagram for a point 1.5 m (5 ft) above the ground at the center of the collector array is shown in Figure 5. A large tree to the east of the house is seen to cause some shading early in the morning. The outline of several small trees along the property boundary to the south are shown but do not cause significant shading at this time. These trees were planted by Mr. Mattson's neighbors after the house was built in order to block objectionable reflections from the collector.

4.0 THE SOLAR SYSTEM

A schematic and control matrix of the Mattson solar system is shown in Figure 6. This figure also shows the locations of transducers used to monitor the performance of this house. The control matrix shows the positions of the three dampers for the primary modes of operation.

A single fan powers the system and three motorized dampers configure the flow. A differential thermostat signals the availability of heat from the collectors. A two-stage thermostat signals demand for heat by the house; the first stage calls for solar heat and the second stage starts the auxiliary gas furnace. Hot air is distributed to the house via an insulated plenum in the crawl space and vents cut through the floor. All ducts are insulated.

The collectors are double glazed and are integrated into the structure of the south wall of the mechanical room. The absorber is unpainted aluminum folded in deep-V, accordion pattern along the vertical run of the collector. The deep V is intended to absorb incident radiation through multiple reflections. Air flows on both sides of the absorber effecting a large heat transfer area. All collector panels are joined at the bottom by a cold air distribution duct and at the top by a hot air collection duct. The panels are, thus, all connected in parallel and flow is from bottom to top. There is a manual summer vent and also a manual damper to connect the collectors to the house for natural convection heating.

The rock bin heat storage is built of concrete block and is located under the mechanical room (see Figure 4). The exterior of the bin is insulated with 2-inch rigid foam; the base is not insulated. The bin is filled with $1\frac{1}{2}$ inch gravel and has a volume of 16.7 m^3 (600 ft^3). A galvanized DHW preheat tank is buried in the rock bin. This tank was not connected at the time of the monitoring.

5.0 PERFORMANCE MONITORING

5.1 Flow Measurements

Duct flow measurements were made in January 1979 as the initial step in the monitoring data. At least five holes were drilled in the ducts at several test sections. A hot-wire anemometer probe was inserted in each hole to three predetermined depths and readings of the mass velocity were taken. On the large ducts, a total of fifteen measurements were made on the cross-section. These velocities were averaged and multiplied by the flow-area to calculate the volumetric flow rate.

Typical results are shown in Figures 7 and 8. These drawings show the locations of the measurement points and the velocity measured at the point. Note that the ducts have insulation on the inside which is 2.5 cm (1 in) thick. Most of the test sections were located in a section of duct that was straight for about 2 m (6 ft) and the flow was relatively steady and the velocity distribution smooth. The accuracy of these measurements was estimated to be 15%.

The flow measurements of Figures 7 and 8 are summarized in Figure 9. The mode of the system was "collector heat direct to house". The measurements show rather large imbalances in flow. The flow out of the collectors is about $2\frac{1}{2}$ times the flow in the inlet duct. The flow entering the plenum under the house is about three times the flow returning in the cold air duct. We repeated these measurements several times with similar results.

Mr. Mattson independently measured the flow rates in some of the same ducts with different instrumentation and his results shows similar imbalances in the input and output flows. He subsequently checked the summer vent, collectors and duct system for major leaks. Since no obvious leaks were found, it was assumed that the leakage must be distributed among the numerous joints, seams and connections in the system. Some of these leaks are apparently within the mechanical room as the pressure in this room is lowered when the fan is on.

There is leakage past all the dampers which complicates the real flow distribution. The crawl space has some observable openings which let in light and must let air out. Mr. Mattson and Energy Alternatives are currently seeking solutions to these problems.

5.2 Data Analysis Flow Approximations

It is impossible to accurately and conclusively define the performance of this system due to the leaks discussed in the previous section. The collector clearly is absorbing solar heat, some of which is delivered to the house and the storage. The variety of immeasurable leaks within the system (dampers) and between the system and its enclosure and/or the ambient atmosphere obviate quantitative description.

As a "best effort" toward analyzing the data we have made the following assumptions:

(1) The average flow rate of the system is 13.8 m^3/min in all modes.

(2) In the collector-to-house mode, the output of the collectors is based on (1) and the temperature entering the crawl space minus the temperature in the collector inlet duct.

(3) In the collector-to-storage mode, the output is calculated as in (2) except the outlet temperature is taken as the air temperature entering the rock bin storage.

(4) In the storage-to-house mode, the temperature of the air entering the crawl space is taken as the outlet and the cold air return to the rock bin as the inlet.

A wood stove was used to provide auxiliary heat through the monitoring period. A temperature probe located behind the wood stove reflected the intensity of the fire. This temperature was used to approximate the heat output of the stove.

5.3 Collector Efficiency Curves

Using the flow approximations described in the previous section, the efficiency curves for the Mattson collector were constructed. This data is shown in Figure 10 along with the HUD reference for this general type of collector. The Mattson collector output was defined as output to the crawl space and, thus, includes penalties for heat losses in the duct work. This may explain the apparent lower efficiency in some ranges.

5.4 Hourly Performance Summary

This section presents selected hourly and daily performance data for the Mattson house between April 10 and June 16. The house was occupied for most of this time and the solar system was operating. The heat balance equations and a description of the itemized data are given in Figure 11 and Table 2. The complete hourly data is given in Appendix I. A single table has been selected to familiarize the reader with the data reduction format.

Table 3 for the day of April 30 illustrates several system modes and will be discussed as an example. During the early morning hours there were no large heat inputs and the house temperature was slowly decreasing. (There was stored heat available from the solar wall because the wood stove had been used on the evening of the previous day.)

At 1 AM, the heat storage outlet, STORE OUT, shows 35°C (95°F) and the collector outlet duct, COLL OUT, shows 26°C (79°F). This indicates a natural convection back flow from the storage bin to the collector during the early morning.

Between 6 AM and 11 AM, the system delivers heat from storage to the house, STORE HOUSE, and the house temperature increases. Note that the collector outlet temperature decreases at this time indicating leakage past damper D1.

At 11 AM, the solar insolation has reached a sufficient level and the collectors start delivering solar heat to the house. The solar radiation is a maximum at 1 PM (13 hours) and the collector outlet is a respectable 73°C (163°F) and the air entering the crawl space is 63°C (145°F). The average air temperature in the crawl space is 30°C (86°F) which would be the air temperature entering the house.

Between 5 and 6 PM, the collectors deliver a small amount of heat to the rock bin storage. Between 9 and 10 PM, stored heat is again delivered to the house. The passive solar wall delivers heat to the house during the first half of the day and absorbs heat during the last half.

The total heat input for this 24-hour period agrees very well with the calculated heat load. This close agreement is fortuitous due to the approximations involved in the calculations. The longer-term agreement of the average of these two quantities indicate that the many assumptions in the data analysis are not too far off.

Further scanning of hourly data in Appendix I show instances when the control system is not operating as it should:

(a) Tables AI-2 to AI-4. SOLAR HOUSE AND STORE HOUSE are zero even though house temperature is low.

(b) Tables AI-5 to AI-7 and AI-10 to AI-12. SOLAR HOUSE is negative because collector fan is running at night.

(c) Tables AI-9 to AI-12. SOLAR STORE shows that system is running at night in this mode, probably cycling briefly.

(d) Tables AI-22, AI-26, AI-29. System did not collect heat even though sun was out and storage was cold.

6.0 OVERALL PERFORMANCE SUMMARY

The performance from April 10 to May 12 is summarized in Tables 4 and 5. Table 4 is a summary of all data contained in Appendix I. These days were selected as best representing the system performance as most of the system was operating most of the time and the house was occupied most of the time. Due to the large number of operational problems during the monitoring period, this data cannot be expected to represent the potential performance of this system.

Table 5 further condenses the data into an overall summary. This data shows that the solar system delivered 15% of the incident radiation to the house. Of the heat put into the heat storage bin only 20% eventually was delivered to the house. Since about half of the collected heat went into the storage, these losses reduce the overall solar fraction.

The second part of Table 5 compares the relative contributions of each of the heat inputs to the total heat required. The calculated heat load is seen to be about 25% greater than the measured total heat input. This could be due to the conservation bias of the calculations, passive solar gain and/or assumptions in the data analysis. Using the total heat input as 100%, the solar contribution is 42%. The electric power and wood stove are 21% and 37% respectively. During the summary period the average house temperature was 14.9°C (58°F) while the average ambient temperature was 5.6°C (42°F).

7.0 PROJECTED ANNUAL PERFORMANCE

In this section the data from the monitoring period is used to project the annual performance of the solar collectors. Table 6 compares solar radiation measured at the Mattson site with simultaneous measurements at the Bozeman High School. The readings agree to within 5 to 10% for weekly averages. These differences could be due to atmosphere variations, reflections and shading variations and instrumentation calibration tolerances.

An overall collector performance curve was drawn from data taken during the monitoring period. This curve is used as a simple model for converting solar insolation to collector output, Figure 12.

Table 7 summarizes the estimate of annual performance. Solar insolation data is taken for the period of July 1978 to June 1979 at the Bozeman High School. Degree day/month data is taken from long-term averages for Bozeman. Based on this data and the simple performance model of Figure 12, solar heat collected and heat loads are shown in Table 7. The annual solar fraction is seen to be 30%. Excess heat is available during the summer which may be used for heating DHW.

8.0 GRAPHICAL PRESENTATION OF DATA

Figures 13 and 14 show graphs of some of the data for ten days early in May. The corresponding data tables for this period are shown in Appendix I, Tables AI-14 through AI-24.

The house air temperature is seen to fluctuate in between 15 and 20°C (59 and 68°F). The passive wall temperature follows the general trends in house temperature but is much smoother due to the higher thermal mass. It appears that the passive wall exchanges heat primarily with the house air. At this time of year the wall receives little solar radiation through the clerestory windows.

The graph of crawl space temperature shows peaks when the solar system or the auxiliary furnace delivers hot air to this space. These peaks correspond to the peaks of solar insolation during the day.

Note that on May 9, Figure 14, the solar system did not operate even though there was adequate solar radiation. This may have been due to a control malfunction. The wood stove was on for most of this day (see Appendix I, Table AI-22) and the passive wall temperature increased. The crawl space temperature during this period shows a small, general decrease in temperature. A slight rise in crawl space temperature corresponds to the peak in house air temperature during late afternoon.

There is no insulation in the floor over the crawl space. The graphs show that there will be heat lost from the house into the crawl space at times when the furnace or the solar system is not delivering hot air to the space. The equilibrium temperature of the crawl space is around 5°C (9°F) below house air temperature.

The owner has changed the design of the heating system since this performance monitoring period. Ducts have been installed beneath the house and the crawl space is no longer used as a plenum. The owner thinks the duct system is an improvement.

9.0 CONCLUSIONS

The Mattson solar system is still in the initial or shake-down phase of operation. The scope of the data base from this monitoring effort is correspondingly limited. Major system problems encountered were (a) large leakage flows, (b) control malfunctions, and (c) a burned-out fan motor. Mr. Mattson has solved some of these problems and is currently taking steps to improve the system. The final performance of the modified system should be much better than the measurements and data contained in this report.

TABLE 1

MATTSON HOUSE HEAT LOAD

	R	U (Btu/hr ft^2 $^\circ$F)	Area (sq. ft.)	U X A
Roof	40.5	.024	2287	56.5
Walls	28.1	.035	2431	85.1
Floor	20	.05	2092	104.6
Windows	1.5	.66	320	211.2
Skylights	1	.975	8.7	8.4
South wall	40.1	.024	637	15.2
*Infiltration:	27,196 ft^3 X 0.5 X .018			244.7
			Total Heat Load	725.7 Btu/hr $^\circ$F or 1.37 MJ/hr $^\circ$C

*Assuming 0.5 air-change/hour

TABLE 2

KEY TO ITEMS IN DATA TABLES

DAILY PERFORMANCE SUMMARY FOR MATTSON HOUSE (ID='II')

REC#	MO	DAY	HR	SOLAR INSO MJ (1)	SOLAR HOUSE MJ (2)	SOLAR STORE MJ (3)	STORE HOUSE MJ (4)	ELECT POWER MJ (5)	STOVE POWER MJ (6)	PASS WALL MJ (7)	TOTAL INPUT MJ (8)	HEAT LOAD MJ (9)	HOUSE TEMP C (10)	COLL OUT C (11)	STORE OUT C (12)	HOUSE IN C (13)	CRAWL SPACE C (14)	AMBNT TEMP C (15)

DESCRIPTION

(1) The total solar radiation intercepted by the collectors.

(2) Solar heat delivered to crawl space based on 13.8m^3/minute flow rate.

(3) Solar heat delivered to storage based on 13.8m^3/minute flow rate.

(4) Solar heat from storage to house based on 13.8m^3/minute flow rate.

(5) Total electric power flowing into house.

(6) Wood stove power estimated as 1.2 ($T_{stove} - T_{house}$)MJ/hr.

(7) Energy change in passive wall mass (+ = delivering heat to house).

(8) Sum of (2) + (4) + (5) + (6) + (7); total hourly energy input.

(9) Calculated heat load based on actual degree-hours and a heat loss factor of 1.37MJ/^{o}C-hr.

(10) Average temperature in house (3 probes).

(11) Temperature in collector outlet duct (average of 3 probes).

(12) Temperature at hot side of rock bin storage (average of 3 probes).

(13) Temperature of air entering crawl space from system (average of 3 probes).

(14) Average temperature of crawl space air (3 probes).

(15) Ambient air temperature.

TABLE 3

*SAMPLE HOURLY PERFORMANCE SUMMARY

DAILY PERFORMANCE SUMMARY FOR MATTSON HOUSE (ID='II')

REC#	MO	DAY	HR	SOLAR INSO MJ	SOLAR HOUSE MJ	SOLAR STORE MJ	STORE HOUSE MJ	ELECT POWER MJ	STOVE POWER MJ	PASS WALL MJ	TOTAL INPUT MJ	HEAT LOAD MJ	HOUSE TEMP C	COLL OUT C	STORE OUT C	HOUSE IN C	CRAWL SPACE C	AMBNT TEMP C	
55	4	30	1	.0	.0	.0	.0	1.0	.0	.0	1.0	21.1	18.2	27.1	35.1	21.5	15.1	3.8	
56	4	30	2	.0	.0	.0	.0	.9	.0	.1	1.0	22.1	17.8	26.7	34.9	21.0	14.7	1.6	
57	4	30	3	.0	.0	.0	.0	1.0	.0	.2	1.2	22.3	17.3	26.4	34.9	20.5	14.4	1.0	
58	4	30	4	.0	.0	.0	.0	1.2	.0	.2	1.4	21.5	16.9	26.1	34.6	20.1	14.2	1.2	
59	4	30	5	.0	.0	.0	.0	1.0	.0	.2	1.2	19.8	16.6	25.7	34.3	19.7	13.9	2.1	
60	4	30	6	1.6	.0	.0	4.1	2.9	.0	.4	7.3	19.3	16.2	23.1	33.9	21.8	14.6	2.1	
61	4	30	7	8.2	.0	.0	16.4	8.0	.0	.2	24.7	17.3	17.1	16.1	32.3	28.2	18.4	4.5	
62	4	30	8	18.1	.0	.0	12.7	7.9	.0	.3	20.9	13.3	17.5	17.5	30.7	27.5	18.6	7.8	
63	4	30	9	42.8	1.1	.0	9.4	5.2	.0	.2	15.8	10.6	18.0	27.1	29.4	28.2	19.0	10.3	
64	4	30	10	44.4	2.0	.0	7.3	4.0	.0	.1	13.5	9.7	17.9	30.0	28.2	28.9	19.4	10.8	
65	4	30	11	102.0	20.6	.0	1.4	3.9	.0	.2	26.1	7.7	18.2	45.0	25.9	39.7	22.2	12.6	
66	4	30	12	149.9	37.4	.0	.0	4.2	.0	-.1	41.5	7.0	19.1	55.0	23.7	55.8	26.5	14.0	
67	4	30	13	156.3	43.1	.0	.0	3.9	.0	-.2	46.9	6.8	20.0	73.0	26.5	62.7	29.2	15.1	
68	4	30	14	151.4	42.9	.0	.0	3.7	.0	-.3	46.3	7.5	21.0	73.0	27.5	63.4	30.4	15.5	
69	4	30	15	75.7	28.0	.0	.0	4.0	.0	-.4	31.6	9.2	21.6	53.0	28.3	49.0	28.5	15.6	
70	4	30	16	69.1	18.3	.0	.0	3.7	.0	-.4	21.6	9.7	21.8	41.6	28.6	39.2	25.9	14.7	
71	4	30	17	49.4	13.6	2.2	.0	4.0	.0	-.5	17.1	10.2	22.2	39.1	29.6	37.6	24.9	14.9	
72	4	30	18	19.7	.0	7.1	.0	3.9	.0	-.4	3.5	10.1	21.9	28.8	28.9	29.8	19.5	14.5	
73	4	30	19	8.2	.0	.0	.0	2.6	.0	-.4	2.3	12.5	21.7	27.1	28.9	26.3	17.8	12.6	
74	4	30	20	.0	.0	.0	.2	2.7	.0	-.3	2.5	16.7	21.4	26.5	29.0	24.7	17.2	9.2	
75	4	30	21	.0	.0	.0	10.2	4.0	.0	-.2	14.0	17.9	20.9	21.6	29.3	27.6	20.2	7.8	
76	4	30	22	.0	.0	.0	6.0	3.5	.0	-.1	9.4	18.9	20.3	20.3	28.5	25.9	19.0	6.5	
77	4	30	23	.0	.0	.0	.0	1.3	.0	.0	1.3	18.5	19.9	24.1	28.2	23.9	16.5	6.4	
78	5	1	0	.0	.0	.0	.0	.9	.0	-.0	.9	19.2	19.5	23.8	28.1	21.8	14.1	5.5	
DAY	4	30	24	896.9	206.9	9.3	67.7	79.3	.0	-1.3	352.7	348.2	19.3	33.6	30.0	31.8	20.7	9.0	SUM-AVG

*Additional Data in Appendix I

TABLE 4

DAILY PERFORMANCE SUMMARY, MATTSON HOUSE

Day	Solar Inso.	Solar House	Solar Store	Store House	Elect Power	Stove Power	Total Input	Heat Load	House Temp	Ambnt Temp
4/10	163	0	12	0	12	20	42	280	10.1	- .1
4/11	899	0	260	0	34	106	137	331	10.9	.8
4/12	1040	0	288	0	35	0	36	323	10.8	1.0
4/13	359	0	45	0	19	146	166	291	11.4	2.6
4/14	920	157	65	0	40	0	196	242	11.9	4.7
4/15	555	91	11	1	57	0	147	213	12.9	6.7
4/16	530	86	28	0	66	0	152	139	13.3	9.4
4/17	973	0	265	0	32	0	30	104	15.1	12.3
4/18	303	0	49	0	19	0	23	313	13.0	4.0
4/19	836	18	145	1	42	0	62	366	12.2	1.3
4/21	1012	242	10	1	56	0	294	302	13.6	4.4
4/22	683	93	49	0	36	179	307	239	13.8	5.3
4/30	897	207	9	68	79	0	353	348	19.3	9.0
5/1	379	0	76	32	54	99	188	419	17.9	5.5
5/2	1080.	232	0	53	85	262	629	481	19.0	4.6
5/3	1057	282	3	1	75	0	357	371	19.2	8.1
5/4	267	67	4	2	70	25	166	237	17.5	10.6
5/5	324	2	2	2	57	134	194	219	18.7	12.4
5/6	316	0	0	0	51	297	348	446	18.0	5.0
5/7	922	226	3	52	60	0	341	410	16.8	4.5
5/8	504	68	1	39	56	451	613	520	16.7	1.1
5/9	928	0	0	0	39	458	494	528	18.5	2.5
5/10	744	181	2	1	73	84	341	417	17.8	5.2
5/11	658	155	4	1	69	0	227	311	17.1	7.9
5/12	676	165	1	5	68	0	237	255	17.7	10.3
TOTALS	17025	2272	1332	259	1284	2261	6080	8105		
							AVERAGE TEMP		14.9	5.6

TABLE 5

OVERALL SUMMARY FOR 25 DAYS*

	MegaJoules	10^6 BTU	%
(1) Total solar insolation	17,025	16.1	100
(2) Solar directly to house	2,272	2.15	13
(3) Solar to storage	1,332	1.26	8
(4) Recovered from storage	259	0.25	1.5
(5) Overall solar efficiency (2)+(4)/(1)			15
(6) Storage efficiency (4)/(3)			20
Calculated house heat load	8,105	7.68	
Total heat input	6,080	5.76	100
Solar input [(2)+(4)]	2,531	2.4	42
Electric power input	1,284	1.22	21
Wood stove input	2,265	2.15	37
Average house temperature	14.9°C	58.1°F	
Average ambient temperature	5.6°C	42°F	

*This period, 4/10 to 5/12, was selected as being most representative of the operation of the solar system.

- -

TABLE 6

SOLAR INSOLATION COMPARISON

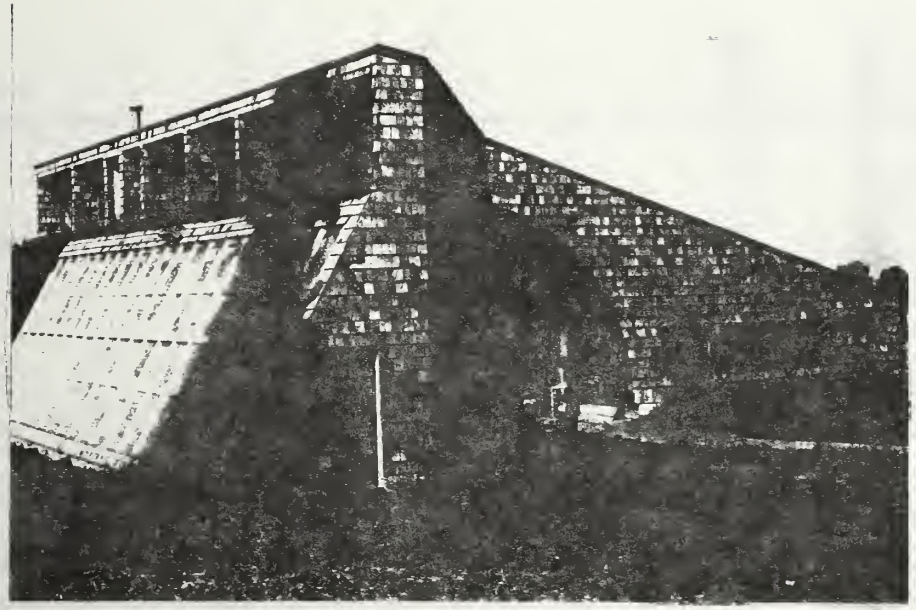
Week Starting	Bozeman High School $kWhm^{-2}$	Mattson $kWhm^{-2}$
4/8/79	3.7	3.9
4/15/79	4.0	4.1
4/29/79	4.0	3.8
5/6/79	(3.6)	3.9

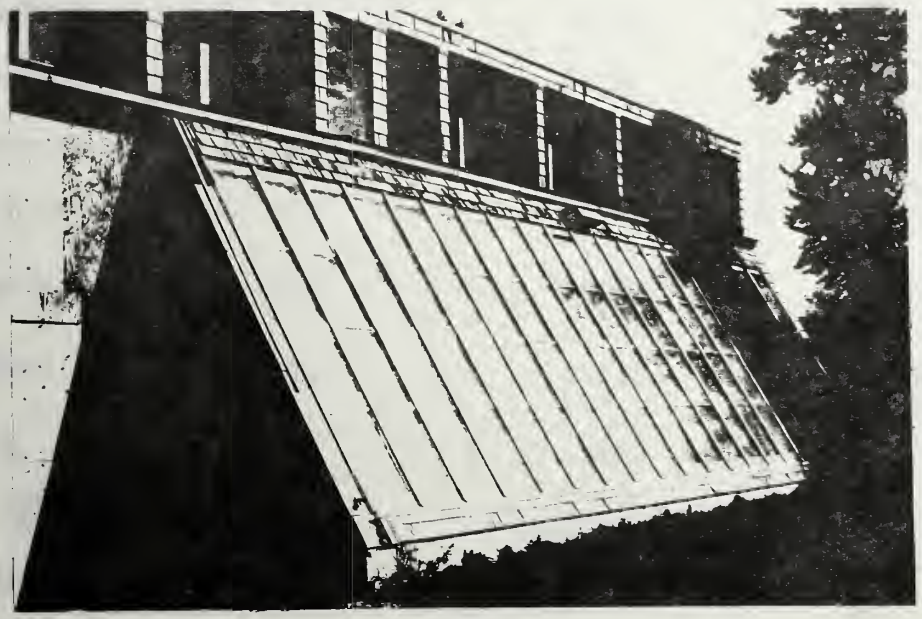
TABLE 7

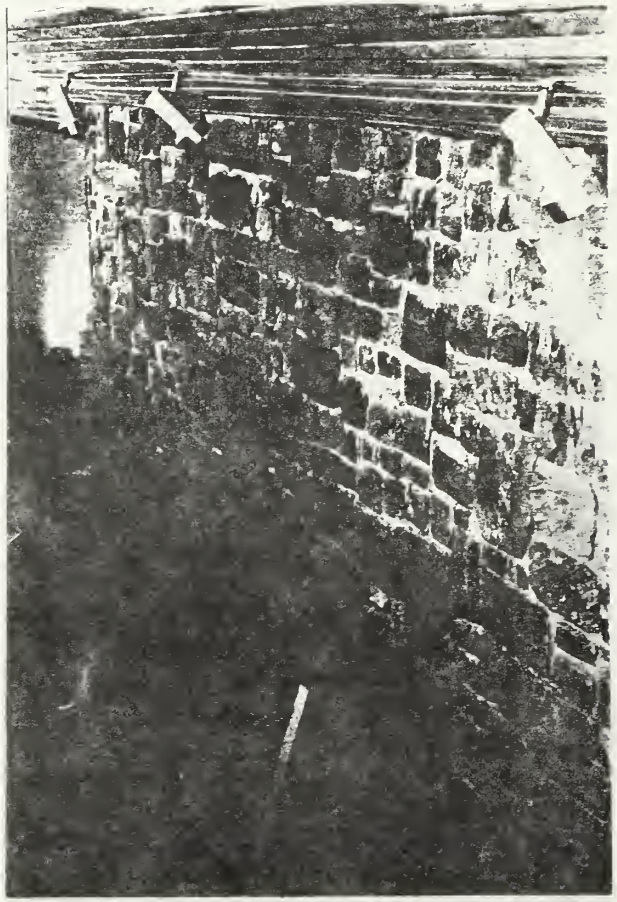
PROJECTED YEARLY PERFORMANCE SUMMARY

Month	Degree Days ^{o}C	Insolation @ 60^{o} kWh/m^2-day	Total Radiation MJ/day	Solar Collected MJ/day	Heat Load MJ/day
July	25	4.65	804	181 *(28)	28
August	38	4.77	825	190 (42)	42
September	160	4.90	848	200 (176)	176
October	322	4.60	796	180	354
November	542	4.81	832	195	596
December	682	3.55	614	118	750
January	762	2.69	465	75	838
February	614	3.39	586	112	675
March	596	3.87	670	140	656
April	377	3.95	683	142	415
May	238	3.75	649	135	262
June	128	4.4	761	172 (141)	141
TOTALS	4484			1484	4933

*Parenthesis indicate maximum solar heat actually used by house; we assume excess heat is vented.

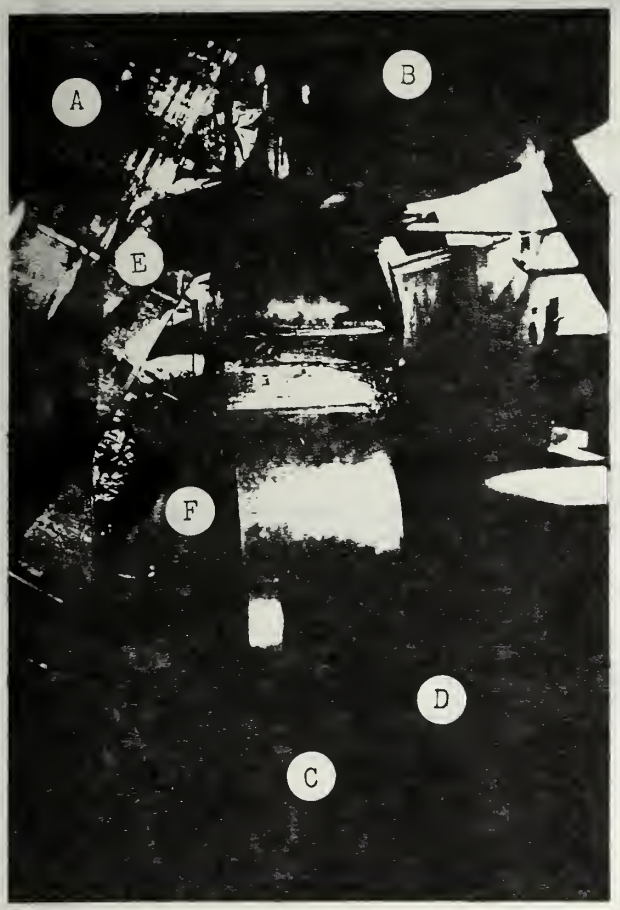






Passive wall

Figure 1: Mattson Solar House



(A) Back side of collectors

(B) Collector outlet

(C) Storage inlet/outlet

(D) To house

(E) From house

(F) Dampers

Figure 2: Mechanical Equipment Room

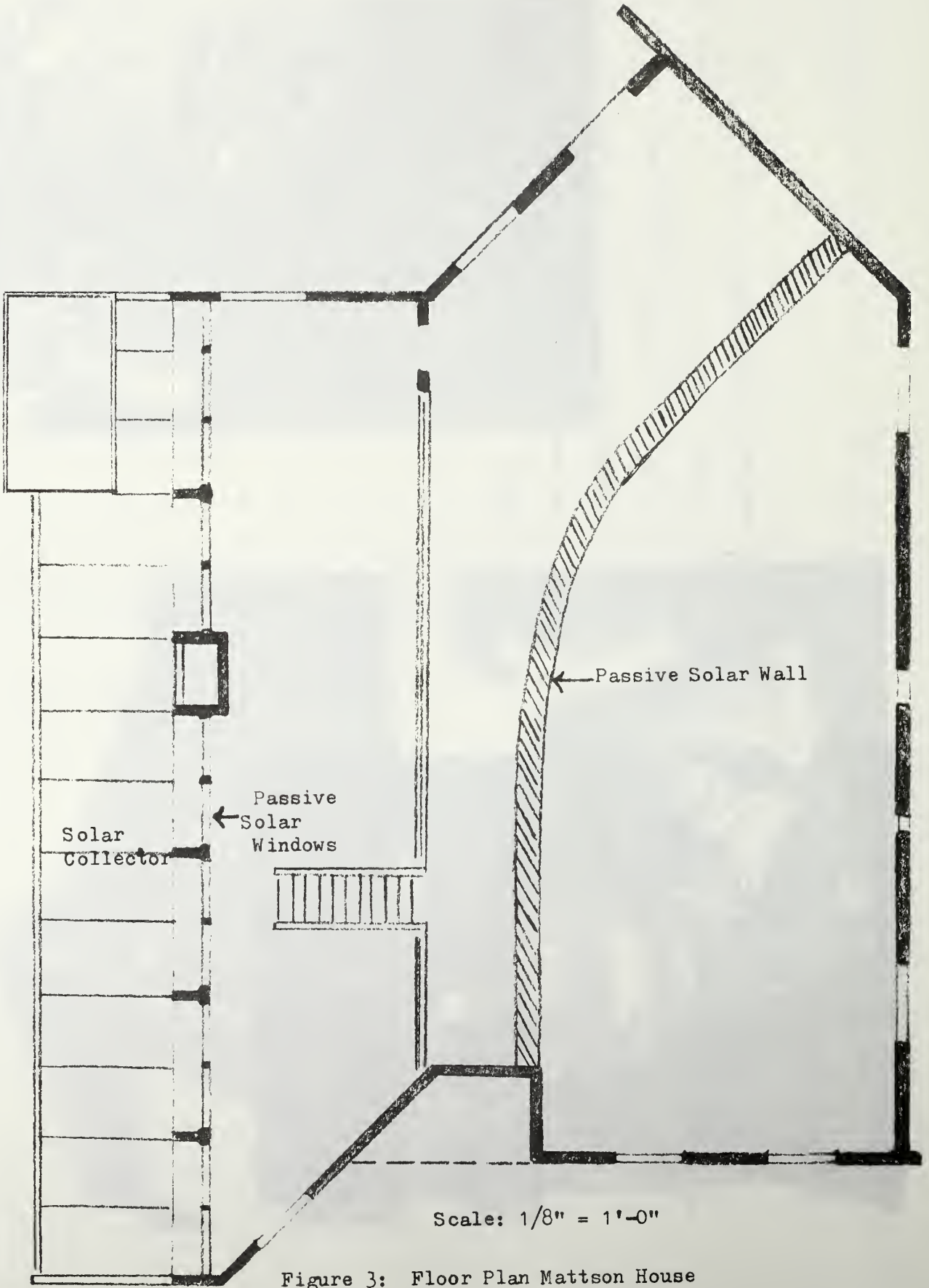


Figure 3: Floor Plan Mattson House

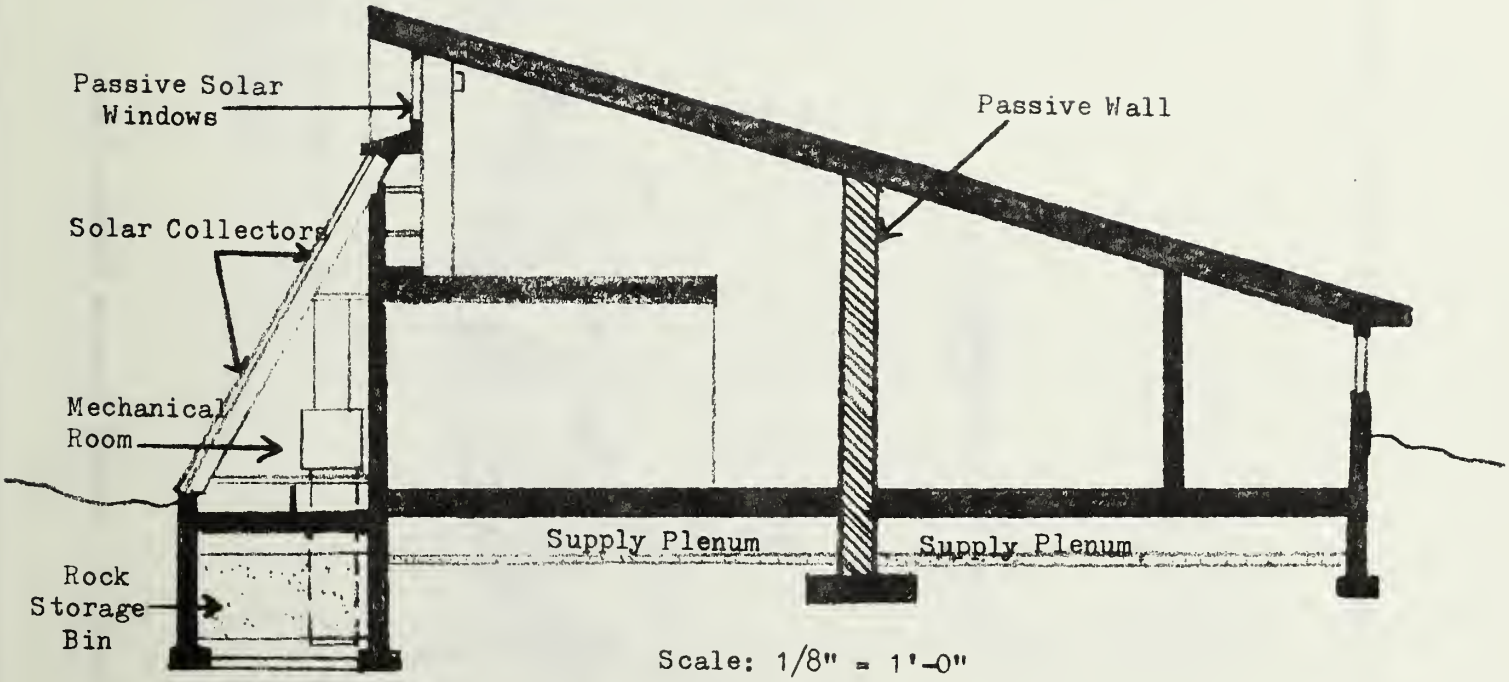


Figure 4: Section - Mattson House

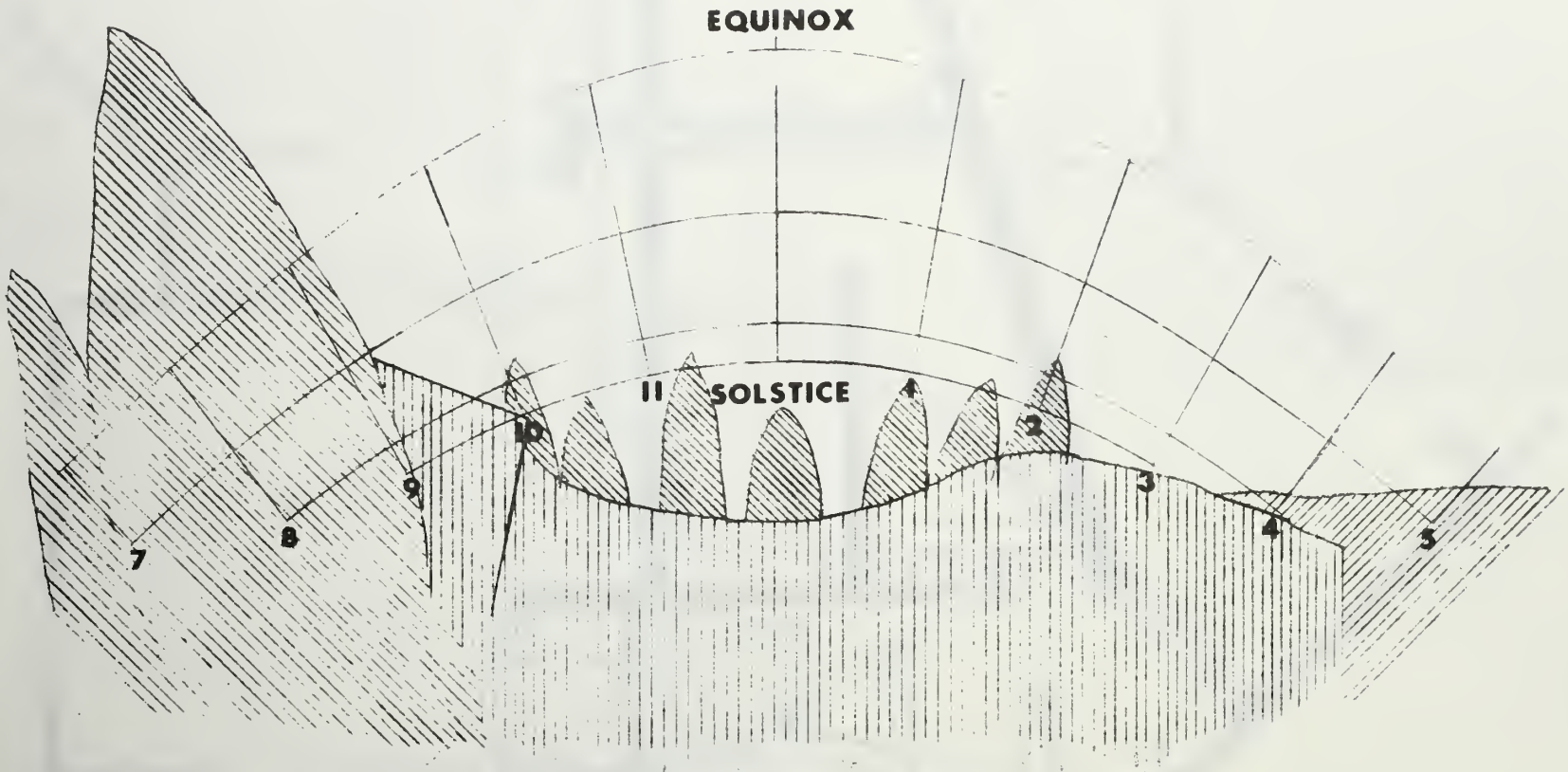
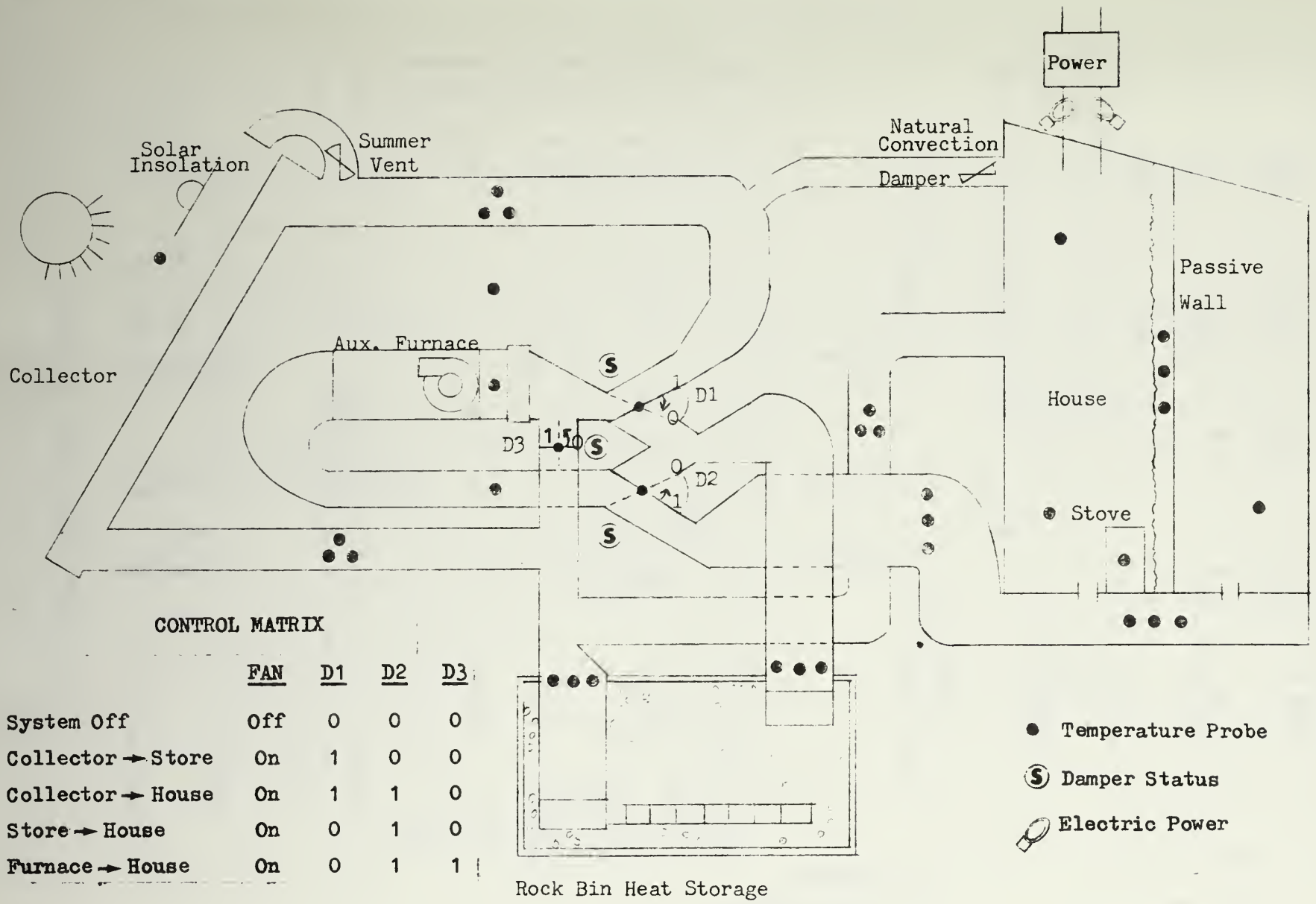


Figure 5: Shading Diagram Mattson House



CONTROL MATRIX

	FAN	D1	D2	D3
System Off	Off	0	0	0
Collector → Store	On	1	0	0
Collector → House	On	1	1	0
Store → House	On	0	1	0
Furnace → House	On	0	1	1

Figure 6: System schematic with transducer layout and control matrix

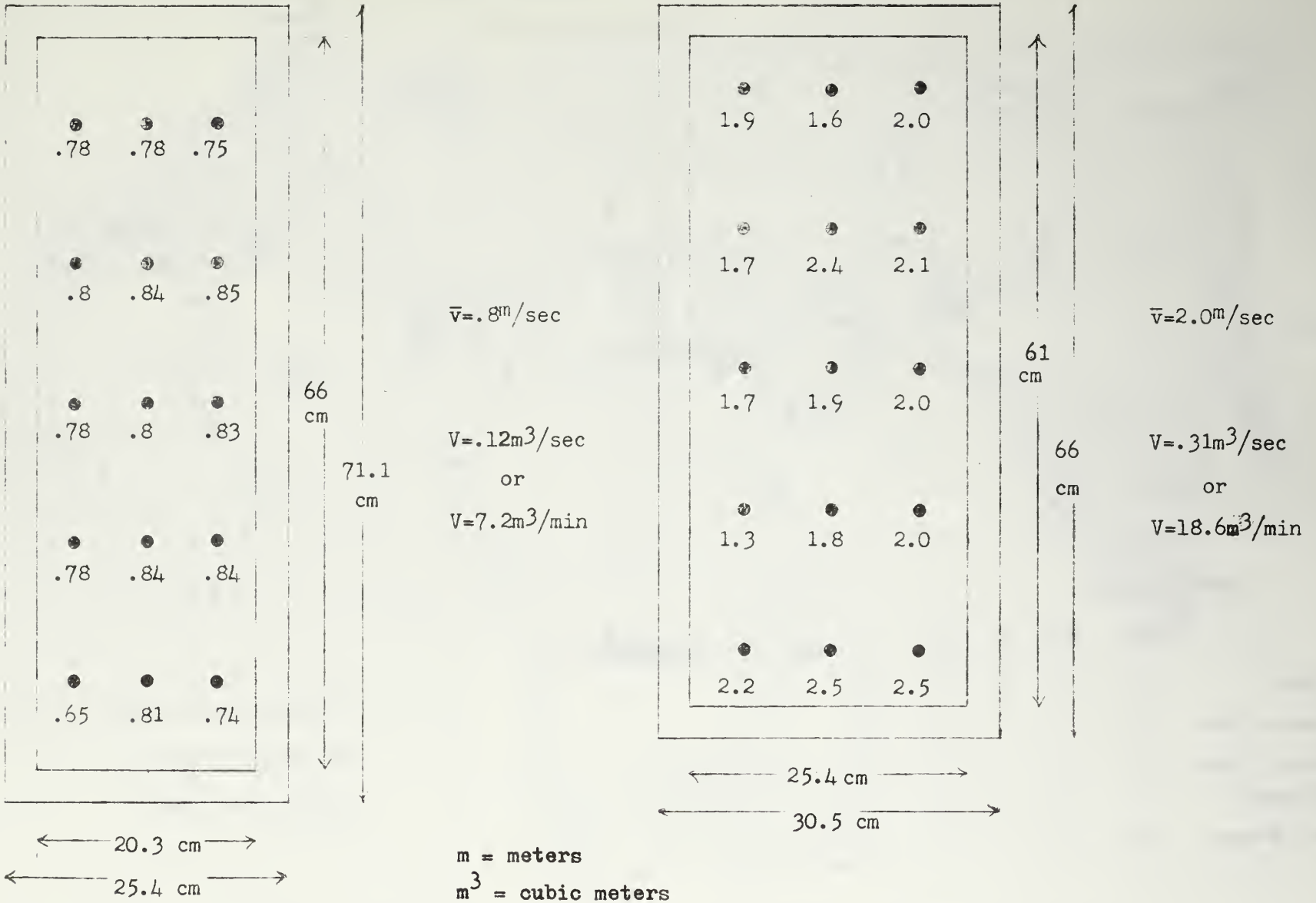
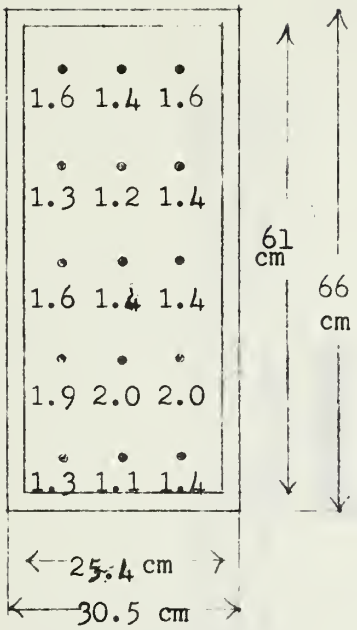


Figure 7: Flow to and from collectors



To House

$\bar{v}$ = 1.5m/sec

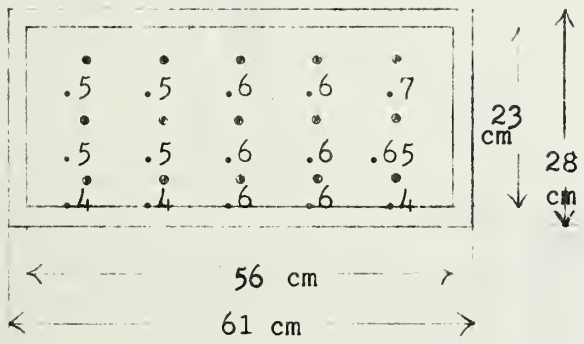
V = .23m^3/sec

or

V = 13.8m^3/min

m = meters

m^3 = cubic meters



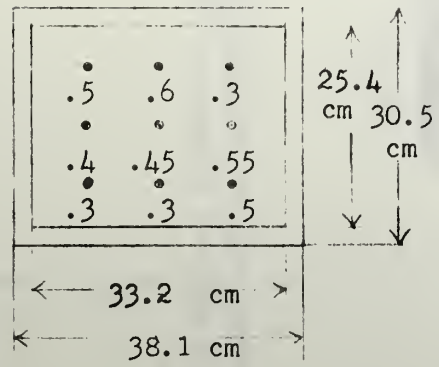
From House

$\bar{v}$ = .54m/sec

V = .07m^3/sec

or

V = 4.2m^3/min



Duct #3

$\bar{v}$ = .43m/sec

V = .04m^3/sec

or

V = 2.4m^3/min

Figure 8: Flow to and from house

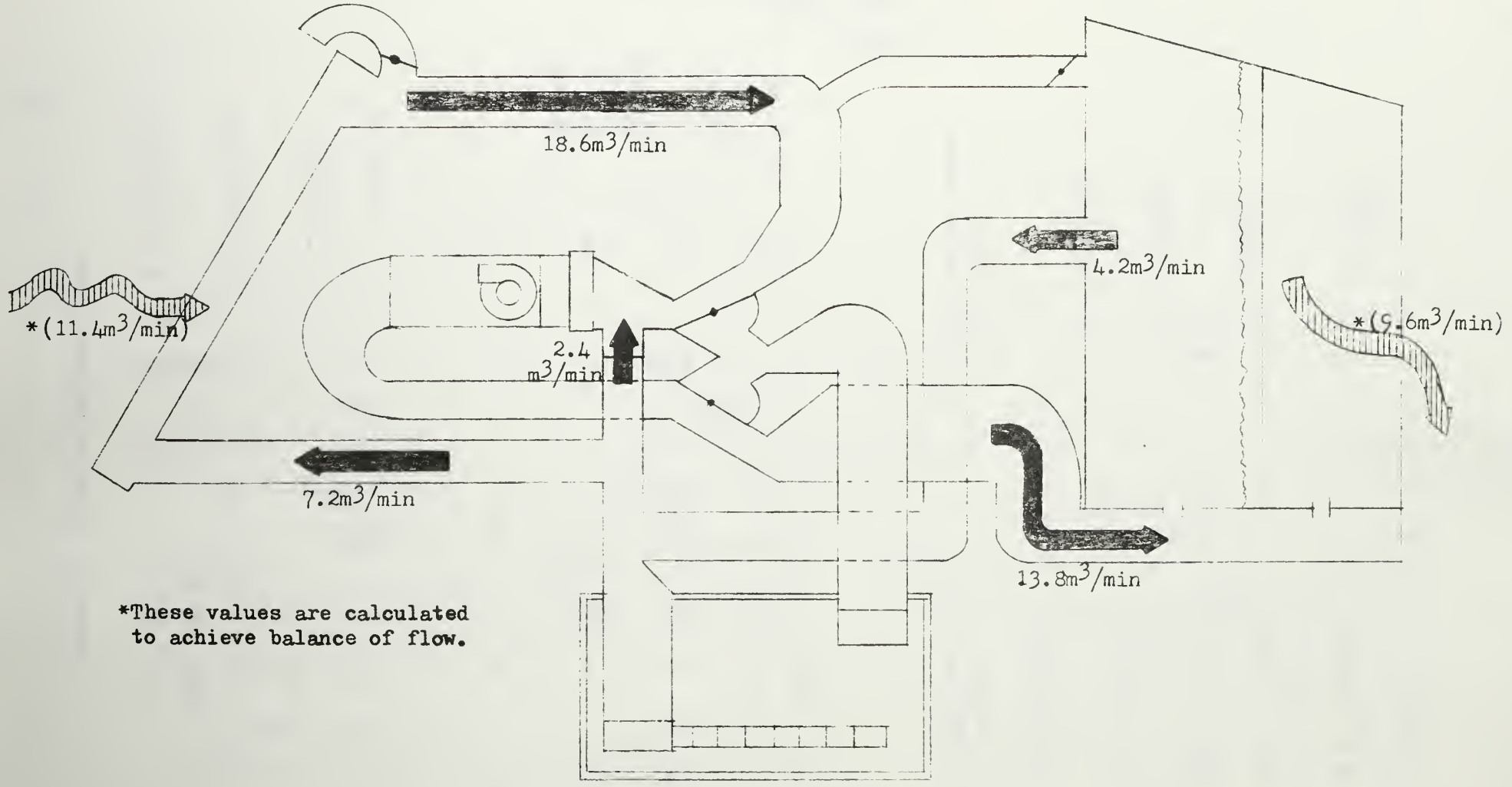


Figure 9: Schematic with flow rates in cubic meters/minute

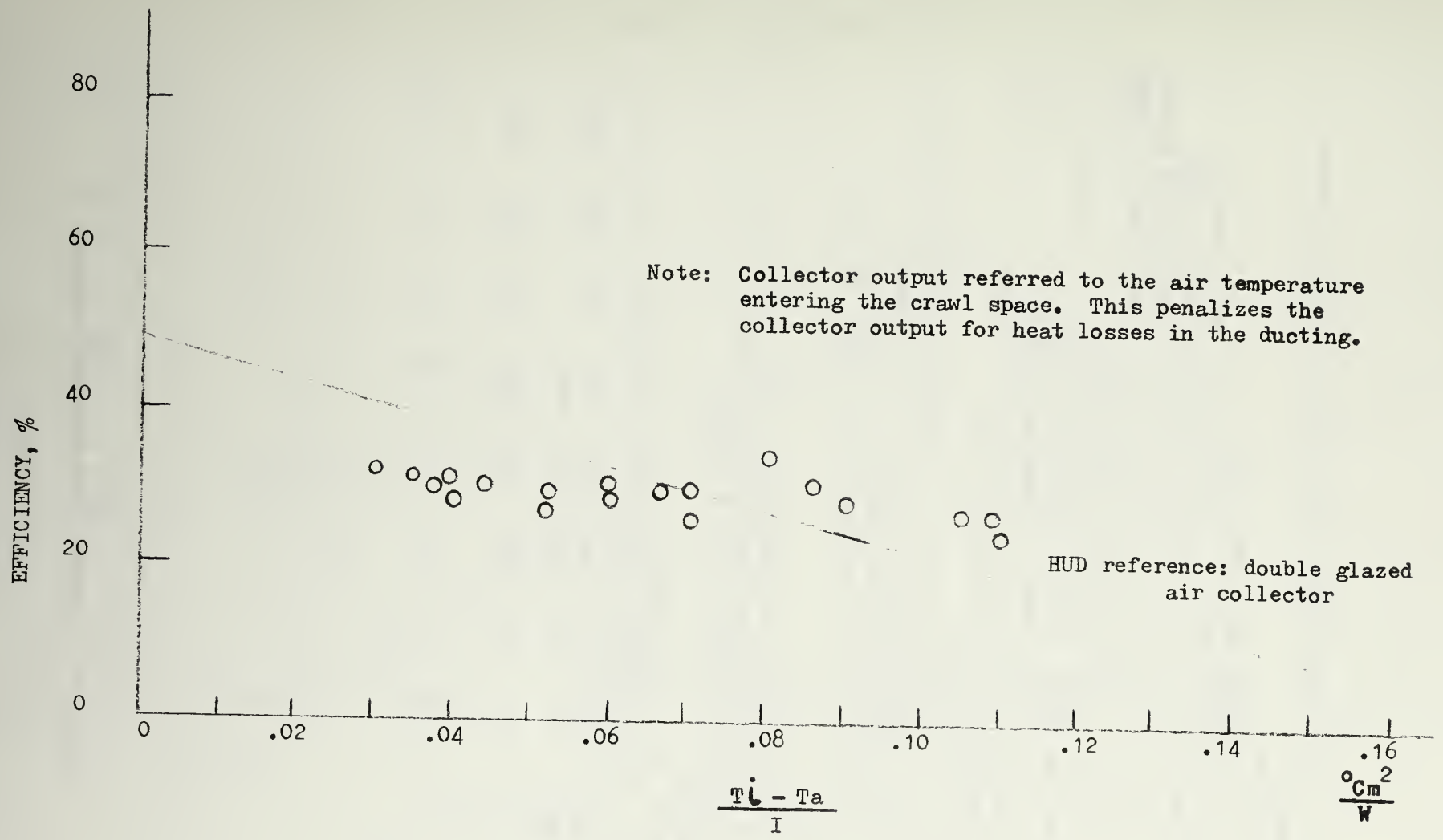


Figure 10: Collector Efficiency Curves

```
3000REM SUBR *** COMPUTE HOURLY SUMS ***********************************
3005 !"-- SUMMING"
3010 N0=N0+1\REM #HRS
3012 REM  ALL THE FOLLOWING ARE IN MEGA JOULES
3015 S(1)=(D(1)+.04)*48.12*3.6*.95   \REM TOTAL SOLAR INPUT CORRECTED
3020 S(2)=D(3)*D(4)*13.8*1.01*1.2*.06*(D(16)-D(15))\REM SOLAR TO HOUSE
3025 S(3)=(1-D(4))*D(3)*13.9*1.01*1.2*.06*(D(17)-D(15))\REM SOLAR TO STORAGE
3030 S(4)=(1-D(3))*D(4)*13.8*1.01*1.2*.06*(D(16)-D(21))\REM STORAGE TO HOUSE
3035 S(5)=D(2)*3.6*.9  \ REM ELECTRICAL POWER,CORRECTED
3040 S(6)=1.2*(D(12)-D(9))\ IF S(6)<3 THEN3041 ELSE3045\ REM STOVE OUTPUT
3041 S(6)=0\REM ZERO STOVE FOR SMALL AND NEGATIVE VALUES
3045 S(7)=1.8*(T1-D(22))\REM PASSIVE STORAGE WALL CHANGE
3050 S(8)=S(2)+S(4)+S(5)+S(6)+S(7)  \REM TOTAL INPUT ENERGY
3055 S(9)=1.37*(D(9)-D(11))\REM HOUSE HEAT LOAD
3059 REM PUT IN TEMPERATURES
3060 S(10)=D(9)\S(11)=D(19)\S(12)=D(17)\S(13)=D(16)\S(14)=D(18)\S(15)=D(11)
3065 T1=D(22)\REM SAVE STORAGE WALL TEMPERATURE FOR DIFFERENCE
3130 !#1,%3I,R,%4I,M0,%3I,D0,%5I,H0,TAB(15),
3140 FOR I=1 TO 15\T(I)=T(I)+S(I)\REM SUM FOR DAY. PRINT HR DATA
3150 !#1,%7F1,S(I),\NEXT\!#1
3160 RETURN\'#1
3200REM *** CALC AVERAGES & FINAL QUANTITIES
3210 FOR I=10 TO15\ REM AVERAGE TEMPERATURES (NOTE HEATS NOT INCL.,)
3220 T(I)=T(I)/N0\REM DAILY AVGS = SUM / NR HRS
3230 NEXT\RETURN
3400REM SUBR *** PRINT REPORT HEADING
3405 !#1\!#1"  DAILY PERFORMANCE SUMMARY FOR  MATTSON HOUSE (ID=",R$,")"
3410 !#1\!#1,"REC# MO DAY  HR ",TAB(16),
3420 !#1," SOLAR  SOLAR  SOLAR  STORE  ELECT  STOVE   PASS  TOTAL   HEAT ",
3430 !#1," HOUSE   COLL  STORE  HOUSE  CRAWL  AMBNT "
3440 !#1,TAB(16),
3450 !#1,"  INSO  HOUSE  STORE  HOUSE  POWER  POWER   WALL  INPUT   LOAD ",
3460 !#1, "  TEMP    OUT    OUT     IN  SPACE  TEMP"
3464 !#1,TAB(16),
3465 !#1,"    MJ     MJ     MJ     MJ     MJ     MJ     MJ     MJ     MJ ",
3466 !#1, "     C      C      C      C      C   . C"
3495 RETURN
```

Figure 11: Computer Heat Balance Equations

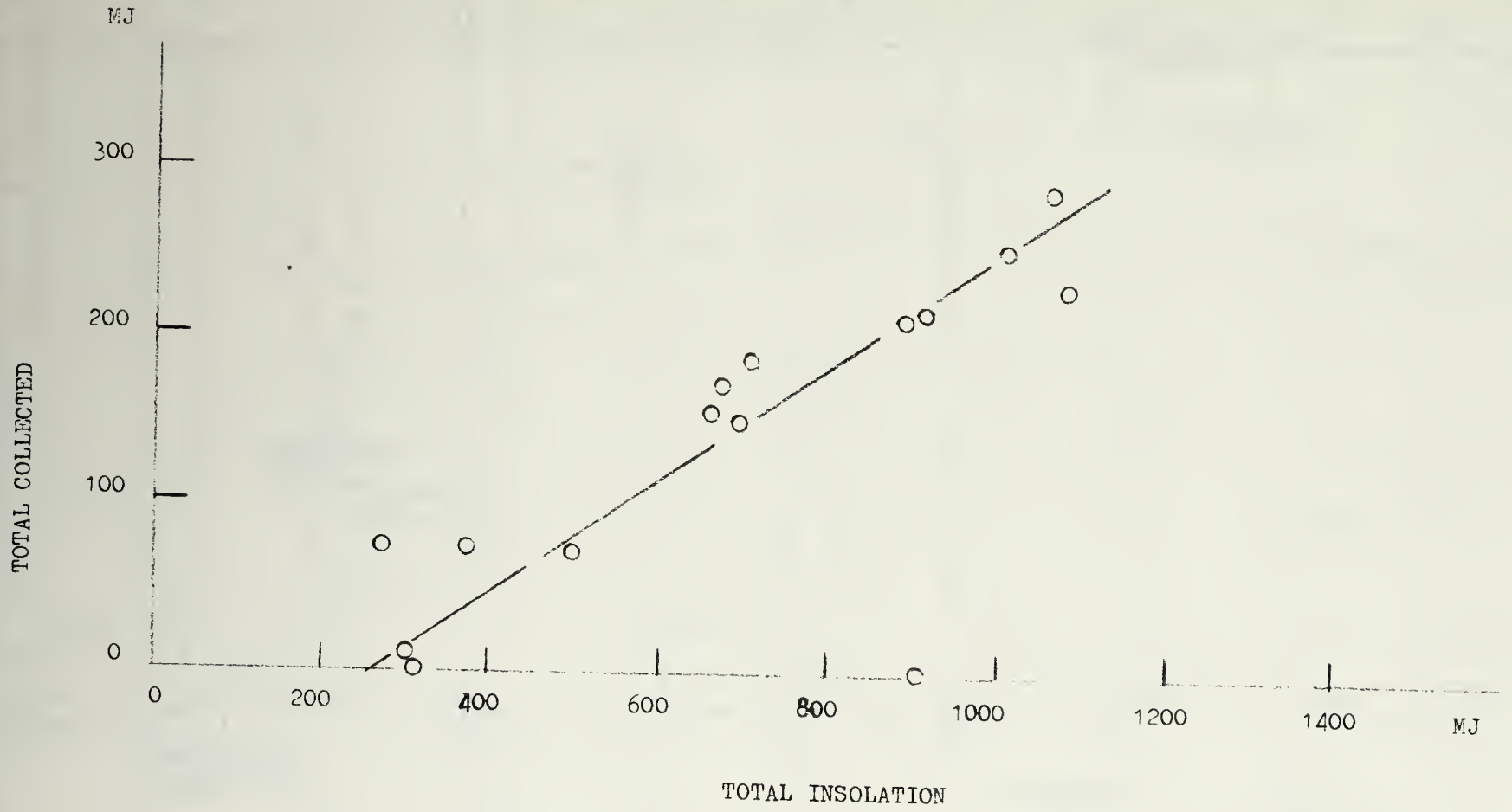


Figure 12: Overall Collector Performance Curve

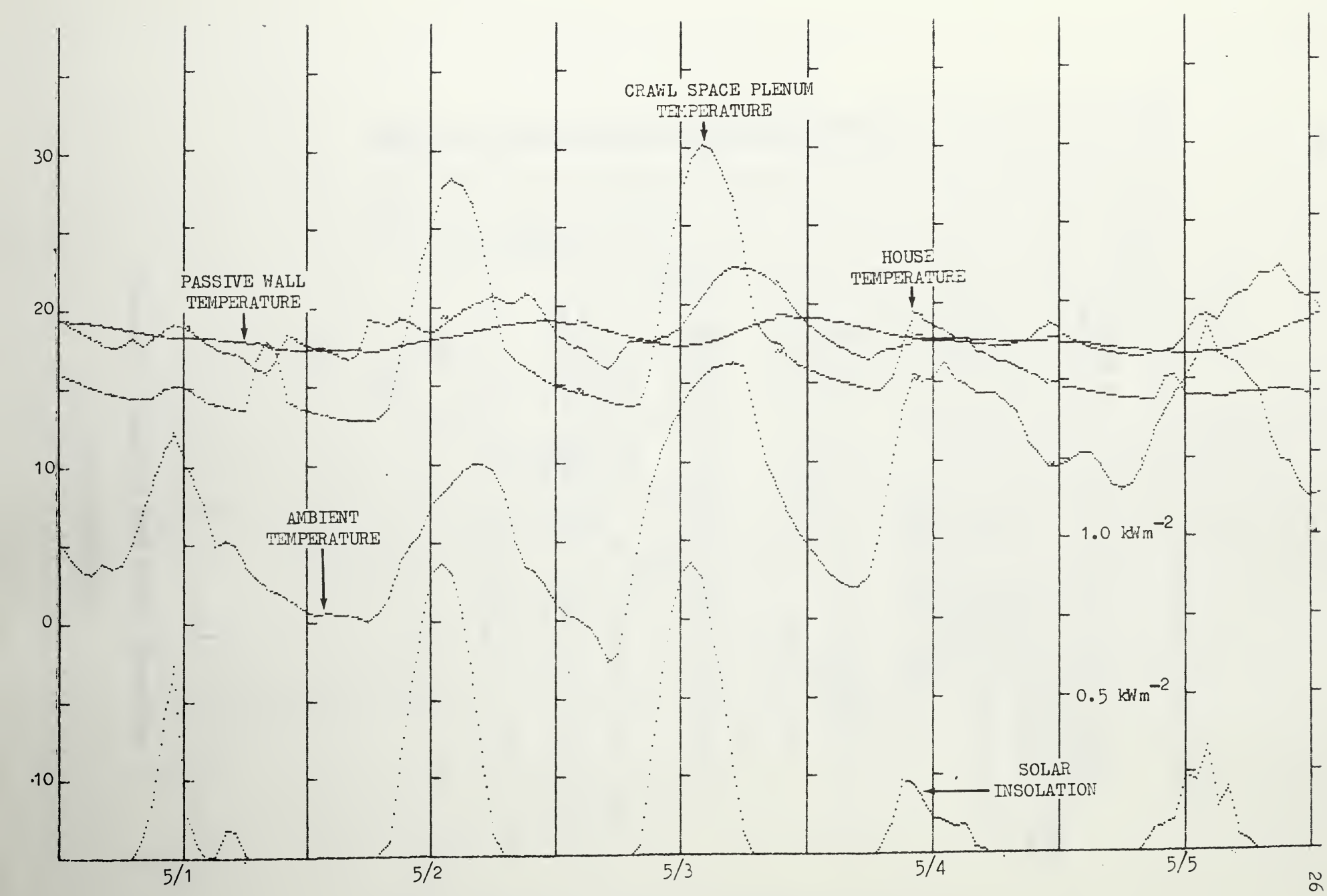


Figure 13: Graph of 5 Days Data in May

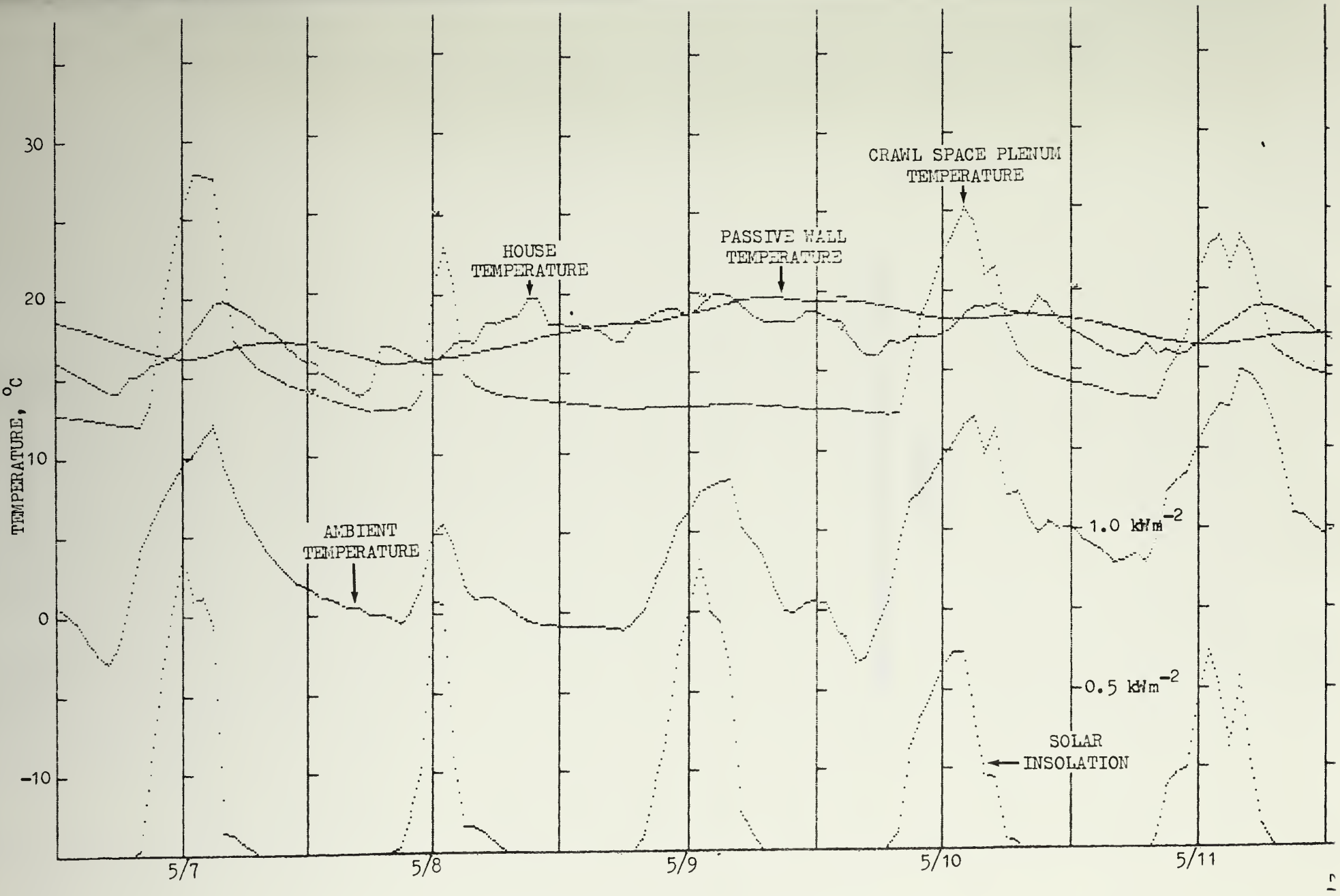


Figure 14: Graph of 5 Days Data in May

APPENDIX 1

TABLES OF HOURLY DATA FOR MATTSON HOUSE

TABLE AI-1

DAILY PERFORMANCE SUMMARY FOR MATTSON HOUSE (ID='I')

REC#	MO	DAY	HR	SOLAR INSO MJ	SOLAR HOUSE MJ	SOLAR STORE MJ	STORE HOUSE MJ	ELECT POWER MJ	STOVE POWER MJ	PASS WALL MJ	TOTAL INPUT MJ	HEAT LOAD MJ	HOUSE TEMP C	COLL OUT C	STORE OUT C	HOUSE IN C	CRAWL SPACE C	AMBNT TEMP C	
435	4	10	1	.0	.0	.0	.0	.4	.0			16.0	11.1	9.3	8.2	9.2	8.2	-.6	
436	4	10	2	.0	.0	.0	.0	.4	.0	.2	.7	15.2	10.8	8.7	8.1	8.7	8.1	-.3	
437	4	10	3	.0	.0	.0	.0	.4	.0	.3	.7	15.1	10.5	8.2	8.0	8.3	8.0	-.6	
438	4	10	4	.0	.0	.0	.0	.4	.0	.3	.7	15.1	10.1	7.8	7.9	8.0	8.0	-.9	
439	4	10	5	.0	.0	.0	.0	.4	.0	.3	.7	14.7	9.8	7.4	7.8	7.7	7.9	-.9	
440	4	10	6	.0	.0	.0	.0	.4	.0	.3	.7	14.6	9.6	7.2	7.7	7.5	7.8	-1.1	
441	4	10	7	.0	.0	.0	.0	.4	.0	.3	.7	14.4	9.3	6.9	7.6	7.1	7.7	-1.2	
442	4	10	8	3.3	.0	.0	.0	.4	.0	.3	.8	13.9	9.1	6.7	7.5	6.9	7.6	-1.1	
443	4	10	9	11.5	.0	.0	.0	.4	.0	.3	.7	12.8	9.0	6.5	7.4	6.7	7.5	-.4	
444	4	10	10	21.4	.0	.0	.0	.4	.0	.3	.7	12.1	9.1	6.6	7.3	6.8	7.6	.2	
445	4	10	11	34.6	.0	.0	.0	.4	.0	.2	.7	11.1	9.4	8.1	6.8	7.4	7.6	1.3	
446	4	10	12	59.2	.0	4.4	.0	1.4	.0	.2	1.6	9.7	10.5	21.4	13.9	11.6	7.6	3.4	
447	4	10	17	18.1	.0	7.5	.0	3.4	9.4			13.9	12.0	12.9	13.4	14.1	9.1	1.8	
448	4	10	18	11.5	.0	.3	.0	.5	6.6	-.2	6.9	14.3	11.5	12.4	14.8	13.0	8.5	1.0	
449	4	10	19	3.3	.0	.0	.0	.4	4.4	-.2	4.6	14.7	10.9	12.9	15.5	12.5	8.3	.2	
450	4	10	20	.0	.0	.0	.0	.4	.0	-.1	.3	15.0	10.4	12.9	15.7	11.9	8.2	-.5	
451	4	10	21	.0	.0	.0	.0	.4	.0	.1	.4	14.8	10.1	12.5	15.8	11.3	8.2	-.7	
452	4	10	22	.0	.0	.0	.0	.4	.0	.1	.5	14.5	9.8	12.2	15.8	10.8	8.1	-.8	
453	4	10	23	.0	.0	.0	.0	.4	.0	.2	.6	14.2	9.5	11.9	15.9	10.4	8.0	-.9	
454	4	11	0	.0	.0	.0	.0	.4	.0	.2	.5	14.0	9.3	11.8	15.9	10.1	7.9	-.9	
DAY	4	10	20	162.9	.0	12.3	.0	12.3	20.4			280.1	10.1	10.2	11.0	9.5	8.0	-.1	SUM-AVG

APPENDIX II

PASSIVE OPERATION OF SOLAR COLLECTORS, MATTSON HOUSE

PASSIVE OPERATION

During the early part of the monitoring period, the Mattsons had not moved into the house and the solar collectors were being operated in the natural convection or passive mode. The natural convection damper, Figure 6, was open and the fan was off. The fan motor was burned out during part of the monitoring period and the system was run in the passive mode.

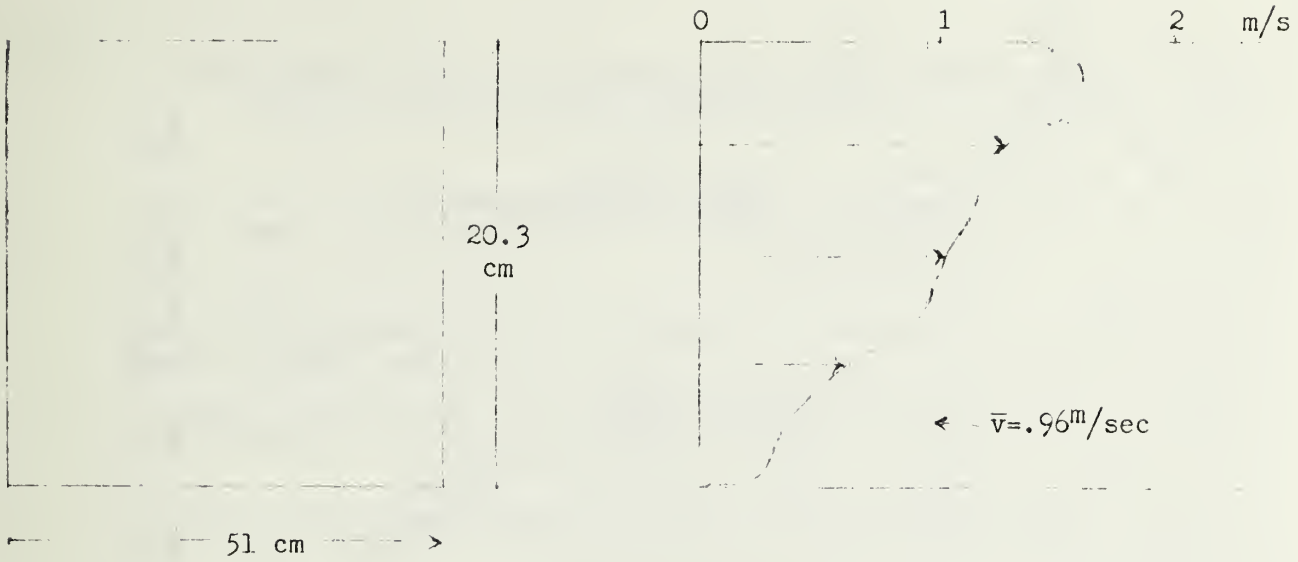
Figure AII-1 shows the results of a single measurement of the collectors' output in the passive mode. This test was done shortly after solar noon on a very clear day near the end of January.

The flow rate out of the duct was 5.93 m^3/min (207 cfm) and the outlet temperature was 105°C (221°F). The incident solar radiation in the plane of the collector was 49.43 kW (15,670 BTU/hr) and the collectors were delivering 11.2 kW (3550 BTU/hr) to the house. The conversion efficiency was 23%.

The computer heat flow equations were modified for the passive mode, Figure AII-2. The passive collector output was calculated using a constant flow rate of 6 m^3/min and the inlet and outlet duct temperatures.

This program produced the results shown in Tables AII-1 through AII-7 for the first week of April. The overall efficiency of the collector during this week was around 10%. The collector output temperature was a maximum of 46.5°C (116°F) on April 8, much lower than the January measurement. I suspect that some of the ductwork or dampers were open in the mechanical room which was diluting the output temperature. During the early part of the monitoring period, the damper blade of D1 was slipping on its shaft and would sometimes be opened 20° or more.

The passive heat was sufficient to maintain the average house temperature around 10°C (18°F) above ambient conditions during this time. This heat came entirely from the passive windows and the collectors.



Sample Calculations: 2:00 pm, January 26, 1979

Duct Area = $0.103 m^2$

Duct Flow = 0.96 m/sec x 0.103 m^2 x 60

= 5.93 m^3/min

INCIDENT POWER = 1.02 kW/m^2 x 48.12 m^2

= 49.43 kW

ABSORBED POWER = $\frac{5.93 \times 1.024 \times 1.2}{60}$ $(105^{\circ}C - 13^{\circ}C)$

= 11.2 kW

EFFICIENCY = $\frac{11.2}{49.4} \times 100 = 22.6\%$

FIGURE AII-1: PASSIVE FLOW PROFILE AND CALCULATIONS

```
3000REM SUBR *** COMPUTE HOURLY SUMS ***********************************
3005 !"-- SUMMING"
3010 N0=N0+1\REM #HRS
3012 REM  ALL THE FOLLOWING ARE IN MEGA JOULES
3015 S(1)=(D(1)+.04)*48.12*3.6*.95\REM TOTAL SOLAR INPUT
3020 S(2)=              6*1.01*1.2*.06*(D(19)-D(15))\REM SOLAR TO HOUSE
3021 IF S(1)>1 THEN 3025 ELSE 3024
3024 S(2)=0
3025 S(3)=(1-D(4))*D(3)*13.8*1.01*1.2*.06*(D(17)-D(15))\REM SOLAR TO STORAGE
3030 S(4)=(1-D(3))*D(4)*13.8*1.01*1.2*.06*(D(16)-D(21))\REM STORAGE TO HOUSE
3035 S(5)=D(2)*3.6*.9  \ REM ELECTRICAL POWER
3040 S(6)=1.2*(D(12)-D(9))\ IF S(6)<3 THEN3041 ELSE3045\ REM STOVE OUTPUT
3041 S(6)=0\REM ZERO STOVE FOR SMALL AND NEGATIVE VALUES
3045 S(7)=1.8*(T1-D(22))\REM PASSIVE STORAGE WALL CHANGE
3050 S(8)=S(2)+S(4)+S(5)+S(6)+S(7)  \REM TOTAL INPUT ENERGY
3055 S(9)=1.37*(D(9)-D(11))\REM HOUSE HEAT LOAD
3059 REM PUT IN TEMPERATURES
3060 S(10)=D(9)\S(11)=D(19)\S(12)=D(17)\S(13)=D(16)\S(14)=D(18)\S(15)=D(11)
3065 T1=D(22)\REM SAVE STORAGE WALL TEMPERATURE FOR DIFFERENCE
3130 !#1,%3I.R,%4I,M0,%3I,D0,%5I,H0,TAB(15),
3140 FOR I=1 TO 15\T(I)=T(I)+S(I)\REM SUM FOR DAY, PRINT HR DATA
3150 !#1,%7F1,S(I),\NEXT\!#1
3160 RETURN\!#1
3200REM *** CALC AVERAGES & FINAL QUANTITIES
3210 FOR I=10 TO15\ REM AVERAGE TEMPERATURES (NOTE HEATS NOT INCL..)
3220 T(I)=T(I)/N0\REM DAILY AVGS = SUM / NR HRS
3230 NEXT\RETURN
3400REM SUBR *** PRINT REPORT HEADING
3405 !#1\!#1"  DAILY PERFORMANCE SUMMARY FOR  MATTSON HOUSE (ID=#",R$,"#)"
3410 !#1\!#1,"REC# MO DAY  HR ",TAB(16),
3420 !#1," SOLAR  SOLAR  SOLAR  STORE  ELECT  STOVE   PASS  TOTAL   HEAT ",
3430 !#1," HOUSE   COLL  STORE  HOUSE  CRAWL  AMBNT "
3440 !#1,TAB(16),
3450 !#1,"  INSO  HOUSE  STORE  HOUSE  POWER  POWER   WALL  INPUT   LOAD ",
3460 !#1, "  TEMP    OUT    OUT     IN  SPACE  TEMP"
3464 !#1,TAB(16),
3465 !#1,"    MJ     MJ     MJ     MJ     MJ     MJ     MJ     MJ     MJ ",
3466 !#1, "     C      C      C      C      C     C"
3495 RETURN
3500REM SUBR *** PRINT SUMMARY DATA
3510 !#1\!#1."DAY",%4I.M1,%3I,D1,%5I,N0,TAB(15),
3520 FOR I=1 TO 15
3530 !#1,%7F1,T(I),\NEXT\!#1," PASSIVE "\!#1
3535 FOR I=1TO 10\!#1 \ NEXT
3540 RETURN
3550END
```

FIGURE AII-2; PASSIVE EQUATIONS

TABLE AII-1

DAILY PERFORMANCE SUMMARY FOR MATTSON HOUSE (ID='I')

REC#	MO	DAY	HR	SOLAR INSO MJ	SOLAR HOUSE MJ	SOLAR STORE MJ	STORE HOUSE MJ	ELECT POWER MJ	STOVE POWER MJ	PASS WALL MJ	TOTAL INPUT MJ	HEAT LOAD MJ	HOUSE TEMP C	COLL OUT C	STORE OUT C	HOUSE IN C	CRAWL SPACE C	AMBNT TEMP C	
267	4	3	1	.0	.0	.0	.0	.4	.0	.4	.7	19.0	9.3	7.3	6.7	7.2	7.0	-4.6	
268	4	3	2	.0	.0	.0	.0	.4	.0	.4	.8	18.6	8.8	6.9	6.6	6.9	6.9	-4.8	
269	4	3	3	.0	.0	.0	.0	.4	.0	.5	.8	19.2	8.4	6.5	6.5	6.6	6.8	-5.6	
270	4	3	4	.0	.0	.0	.0	.4	.0	.5	.9	23.0	8.0	6.2	6.4	6.3	6.7	-8.8	
271	4	3	5	.0	.0	.0	.0	.4	.0	.5	.9	21.6	7.6	5.9	6.3	5.9	6.5	-8.1	
272	4	3	6	.0	.0	.0	.0	.4	.0	.6	.9	18.8	7.3	5.6	6.3	5.5	6.5	-6.4	
273	4	3	7	.0	.0	.0	.0	.4	.0	.5	.9	18.1	7.0	5.4	6.2	5.3	6.4	-6.2	
274	4	3	8	3.3	3.7	.0	.0	.4	.0	.6	4.6	17.2	6.8	5.3	6.1	5.2	6.3	-5.8	
275	4	3	9	14.8	2.9	.0	.0	.4	.0	.5	3.8	15.2	6.8	5.2	6.1	5.1	6.3	-4.3	
276	4	3	10	42.8	1.3	.0	.0	.4	.0	.5	2.2	13.2	7.3	5.3	5.9	5.2	6.3	-2.4	
277	4	3	11	67.5	2.2	.0	.0	.4	.0	.4	3.0	13.2	9.6	9.6	5.2	6.1	6.3	.0	
278	4	3	12	134.9	6.4	.0	.0	.4	.0	.2	7.0	14.6	13.0	20.3	6.0	6.6	6.3	2.3	
279	4	3	13	116.8	9.8	.0	.0	.4	.0	.0	10.2	15.6	15.0	29.3	7.1	7.0	6.4	3.6	
280	4	3	14	110.3	8.7	.0	.0	.4	.0	-.3	8.9	16.0	15.0	27.6	8.0	7.4	6.6	3.3	
281	4	3	15	130.0	9.9	.0	.0	.5	.0	-.5	9.9	17.0	16.0	31.2	8.7	7.8	6.7	3.5	
282	4	3	16	131.7	10.4	.0	.0	.4	.0	-.7	10.1	17.5	16.7	32.9	9.5	8.2	6.9	3.9	
283	4	3	17	72.4	7.9	.0	.0	.4	.0	-.7	7.6	17.2	16.1	27.5	9.9	8.7	7.0	3.6	
284	4	3	18	39.5	4.9	.0	.0	.4	.0	-.7	4.6	16.3	14.4	20.6	10.0	9.0	7.1	2.5	
285	4	3	19	13.2	2.9	.0	.0	.4	.0	-.6	2.7	15.8	12.6	15.7	9.3	9.1	7.1	1.1	
286	4	3	20	3.3	1.5	.0	.0	.4	.0	-.4	1.5	15.1	11.3	12.1	7.6	9.3	7.1	.3	
287	4	3	21	.0	.0	.0	.0	.4	.0	-.1	.3	14.0	10.3	9.8	7.2	8.9	7.0	.1	
288	4	3	22	.0	.0	.0	.0	.4	.0	.1	.5	14.2	9.8	8.4	7.0	8.2	7.0	-.6	
289	4	3	23	.0	.0	.0	.0	.4	.0	.3	.6	13.6	9.3	7.4	6.8	7.6	6.9	-.7	
290	4	4	0	.0	.0	.0	.0	.4	.0	.3	.6	13.1	8.9	7.0	6.7	7.2	6.9	-.7	
DAY	4	3	24	880.5	72.6	.0	.0	8.8	.0	2.6	84.0	397.3	10.6	13.3	7.2	7.1	7.0	-1.6	PASSIVE

PROCEEDINGS OF THE INTERNATIONAL SOLAR ENERGY SOCIETY
SILVER JUBILEE CONGRESS
Atlanta, Georgia - May 1979
VOLUME II

MEASURED PERFORMANCE OF A PASSIVE SOLAR RESIDENCE IN BOZEMAN, MONTANA

Charless W. Fowlkes
Fowlkes Engineering
31 Gardner Park Dr.
Bozeman, MT 59715

ABSTRACT

This paper summarizes the thermal performance of a passive solar house. Hourly data taken over a three month period during one of the coldest winters on record showed that the solar system was providing 65% of the heating load. The average house temperature was 19° C and the average daily variation was 6.4° C. A low-cost data acquisition system utilizing a Radio Shack TRS-80 computer was developed for this project.

1. INTRODUCTION

We originally intended to present performance data on a passive solar house and a nearby active air solar house in this paper. During the test period the recently completed active house experienced a fan failure as well as some control problems. Flow measurements indicated very large imbalances of flow in both the collector and house loop apparently due to air leaks in the collectors and dampers. Because of these problems the active house data was judged to be of limited value and is not presented in this paper.

2. PASSIVE HOUSE DESCRIPTION

The passive solar house is located in Bozeman, MT at an elevation of 1460 m in a broad mountain valley. Environmental data are shown in Table 1. The house was designed and built by the author during 1976-77 and it has been occupied by the author and his family since September 1977. A photograph of the house is shown in Figure 1.

The house is a two-story wood-framed structure with a usable floor area of about 190 m^2. The walls are framed with 5x15 cm studs on 60 cm centers and the roof is spanned by 5x25 cm purlins. The walls and the floor are insulated with 15 cm-thick glass fiber batts and the roof with 25 cm-thick batts. A continuous vapor barrier of polyethylene was used inside all insulated surfaces.

Table I: Bozeman Climatological Data (1)

	Deg. Day Avg. °C-d	Deg.Day 1978-79 °C-d	Insol. 1977-78 kWh/m^2-d	Insol. 1978-79 kWh/m^2-d (60°)
Oct	322	-	4.41	5.24
Nov	542	-	1.99	2.92
Dec	682	864	1.93	2.35
Jan	762	1019	2.53	2.8
Feb	614	730	3.81	3.48
Mar	596	-	4.98	3.97

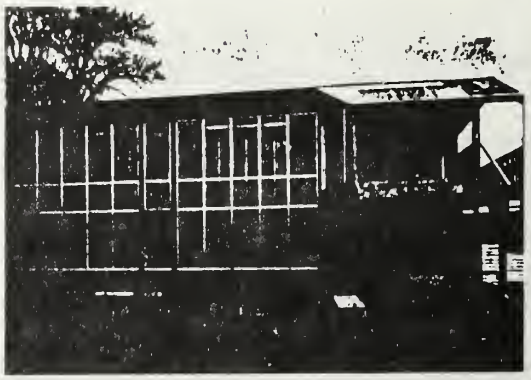


Fig. 1: Passive solar house

Fenestration, excluding the collector glazing is 12% of the floor area and all windows are double glazed. Electricity is used for lighting, hot water and all appliances.

2.1 Passive Solar System Description

Radiation enters a vertical, double-glazed aperture which faces due south. The total area of the aperture is 43.6 m^2. The center 4m^2 is not backed by the solar wall and serves as a window.

The solar wall consists of 20 vertical tubes filled with water. The tubes are filament wound FRP, 40 cm in diameter, 5.2 cm long and contain 674 kg of water each. The total

storage mass of the wall is about 13,480 kg. The tubes are painted flat green on the portion facing the sun and are spaced 3.5 cm apart. Heat is transferred from the solar wall to the house by natural convection and radiation.

Design calculations indicated that a movable insulation system would be needed to control the heat loss through the collector glazing at night. The insulation system selected for this house consists of two thick fabric curtains which resemble window shades, Figures 2 and 3. The curtains are mounted on a common shaft and actuated by a geared electric motor. The outside of the curtain was fabricated from 6 oz. white, dacron sailcloth and the inside from 6 oz. nylon "pack cloth" having a urethane coating. The insulation consists of 4 layers of 10 oz. Polarguard, a continuous polyester fiber. The thickness of the curtain is about 12 cm. Sewn along both vertical edges of the curtain is a bolt rope which runs in a continuous plastic guide attached to the window frame to minimize heat loss by convection around the edges.

Fig.2: Storage wall and curtain

1. Water storage wall
2. Glazed aperture
3. Insulating curtain
4. Auxiliary hot air
5. Cold air return
6. First floor
7. Second floor

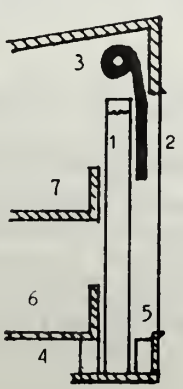


Fig. 3: Schematic of passive solar system

The calculated average heat load for the house using ½ air-changs/hour is 1.08 MJ/h°C (1.41 MJ/h° C with insulating curtain open; 0.9 MJ/h° C closed). The heat load for the house with the collector wall replaced by a conventional wall is 0.90 MJ/h° C.

2.2 Auxiliary Wood Furnace

The auxiliary heat is supplied by a wood burning furnace. The heat from the furnace is normally directed to the solar storage wall. The furnace always operates at full output with the storage wall acting to moderate the amount of furnace heat entering the house itself.

The furnace consists of a fire box and a heat exchanger. It was designed by the author and fabricated from 11 and 13 gage steel sheet. The fire box is lined with fire brick and is a base burning design. Preheated air enters the combustion chamber through three adjustable vents. The combustion gases leave the fire box below the grate and pass through a heat exchanger. A draft induction fan is used when starting a new fire. Heat is moved from the furnace to the solar wall with an air loop powered by a conventional furnace blower and thermostat. The only hot air outlets to the house are at the base of the solar storage wall. The cold air returns from a manifold located on the other side of the solar wall.

If the house temperature drops to around 15° C and cold and cloudy weather is predioted a fire is built. The fire box is filled with about 75 kg of pine and ignited. The furnace reaches full output during the next half hour and burns for about 6 hours. A second load of fuel is sometimes added to the fire box in extreme weather.

3. TEST RESULTS

3.1 Introduction

The data acquisition system, transducers and data accuracy are discussed in the Appendix. Hourly data was processed to calculate hourly average powers and temperatures. The basic balance equation was Power Input = Power Output + Storage Power. Four Power inputs were considered: solar power on storage wall, solar power directly into house, furnace power into house and electrical power dissipation in the house.

Solar insolation was measured on a vertical plane insido the glazing. Solar power on the storage wall is calculated by multiplying this insolation by the aperture area and the fraction of time the insulating curtain was open during that hour. Solar power directly into the house wan calculated from the insolation times the area of the south facing

windows. Furnace power was caloulated from the inlet and outlet temperatures and flow rate. Electrical dissipation was estimated as 0.6 of the total electrical power coming into the house.

Storage power was considered from two sources: energy changes in the solar wall and energy changes in the house itself. Solar wall power was calculated from the mass, specifio heat and average temperature change of the water per hour; 52 MJ/° C x Δ T/h. The house storage power was estimated as 8 MJ/° C x ΔT/h.

The output power was calculated from the six quantities above and divided by the temperature difference between the house and ambient air to produce a heat load factor.

3.2 Daily Performance

Sample hourly data in Tables II and III illustrate the thermal behavior of the system on two different days. Typically during the early morning hours the temperatures of the tubes decrease as they deliver power to the house and the house temperature reaches a minimum around sunrise. The sun charges the tubes and heats the house during the day and both tubes and house reach a maximum near sunset. The tubes are normally 3 to 9°C above the house. This difference depends on the heat load since the heat is removed from the tubes by natural convection. Similarly the temperature variation in the house is usually greater for low ambient temperatures. The overall heat transfer coefficient between the tubes and the house was around 21 KJ/hm^2 °C.

Table II: January 8, very cold and clear

TIME h	SOLAR POWER MJ/h	TUBE POWER MJ/h	TUBE TEMP °C	HOUSE TEMP °C	AMB. TEMP °C
12 am	0	-18.4	25.0	16.7	-27.8
4 am	0	-12.7	23.7	14.9	-27.2
8 am	0	-19.9	22.1	13.9	-26.1
12 pm	109.2	47.3	23.0	18.7	-16.4
4 pm	38.1	45.1	28.0	22.4	-16.4
8 pm	0	-15.9	27.0	19.3	-24.1
12 am	0	-17.5	25.6	17.5	-23.7
24 Hour Total			24 Hour Average		
	637.1	32.6	24.8	17.7	-22.5

In Table II the 24 hour net tube energy for January 8 was + 32.6 MJ; enough reserve energy to heat the house for about two hours. The previous 6 days were similarly cold but clear and the house was 100% solar. During this period the daily collector efficiency was around 50%. January 9 was cloudy and the furnace was fired at 11 am when the house temperature dropped to 15.8° C.

Table III: March 1, a olear moderate day

TIME h	SOLAR POWER MJ/h	TUBE POWER MJ/h	TUBE TEMP °C	HOUSE TEMP °C	AMB. TEMP °C
12 am	0	- 8.3	22.4	17.2	- 7.7
4 am	0	- 7.6	21.5	16.0	- 7.4
8 am	0	- 5.7	20.8	16.3	- 4.7
12 pm	116.8	52.9	22.3	21.0	- 1.9
4 pm	21.6	24.4	27.3	23.5	- 5.2
8 pm	0	-10.1	26.7	20.7	-10.3
12 am	0	- 9.5	26.1	19.6	-14.9
24 Hour Total			24 Hour Average		
	540.4	194.0	23.7	19.2	- 7.0

From Table III the 24 hour net energy for March 1 was 194 MJ or enough to supply the house for another 24 hours without sun or auxiliary power. The average collector efficiency was 54% on this day.

3.3 Performance During Monitoring Period

Hourly data was recorded between November 28 to March 6. The heating degree days during the test period were 17% above average creating a challenging test environment. The average house temperature was 19.0° C with an average differential of 3.7° C between the upper and lower floor. The average daily variation in house temperature was 6.4° C.

During the test period electrical power dissipated in the house was 7.7 GJ. Thirteen fires were built in the auxiliary wood furnace which put a total of 10.3 GJ into the house (about 0.8 cord of pine was consumed). The total heat requirement of the house was 52 GJ based on the experimental heat loss factor of 0.83 MJ/h-°C. Based on these measurements the sun provided 34 GJ or 65% of the total heating energy during December, January, and February.

Measurements of the temperature drop across the insulating curtain implied that its overall heat transfer coefficient was 4 KJ/hm^2 °C. This value is much larger than anticipated and may be due to convection caused by inadequate sealing around the edges of the curtain.

The average efficiency of the furnace was determined by weighing the total wood put in during each firing and then measuring inlet and outlet duct temperatures and outlet flow rate. The heating value of the wood was taken as 18.4 MJ/kg. Using these data the average overall efficiency of the wood furnace was 58.7% during 11 test firings.

3.4 Projected Annual Performance

During the entire heating season a total of 16 fires were built in the auxiliary wood

furnace, the first on November 11 and the last on January 27. A total of 1140 kg (about one cord) of wood was burned producing an estimated 12.7 GJ of heat. The annual electric power, dissipated as heat into the house, contributed about 15 GJ (700 kWh/mo). Using an average degree-day's value of 4484 the annual heat load of the house would have been 90 GJ and the annual solar fraction, 69%. Since the test period this winter was 27% colder than normal, the average annual solar fraction is probably about 79%.

The insulating curtain is kept in the raised position from May to October. No overheating occurs during the summer but on warm and sunny fall days excess heat must be vented for comfort.

4. SUMMARY

The test results show that this system provides a high percentage of the house heat load by solar conversion, even during extremely cold weather. It seems unlikely that the overall solar fraction could be significantly improved by economically admissable changes in either aperture area or storage thermal capacity (2,3,4). The conversion efficiency of the wood furnace and the heat loss factor of the house itself could not be greatly improved. Reductions of over 10% in the overall heat loss would result if the movable insulation could be constructed so as to have a heat transfer coefficient equivalent to a normal wall. A reduotion in the 24 hour temperature variations would increase the comfort of the house.

The TRS-80 data acquisition system performed to our satisfaction. It provided a large and densely sampled data base from which to construct this performance summary.

5. ACKNOWLEDGEMENT

The work described was supported by a grant from the Alternative Renewable Energy Sources (ARES) Program of the Montana Department of Natural Resources and Conservation. This grant program derives operating revenue from a severance tax on coal mined in Montana and is dedicated to promoting "researoh, development and demonstration of renewable energy resources". The cooperation and support of Dana Gunderson, Project Monitor, is acknowledged. Pat Sullivan is acknowledged for typing and editing this manuscript.

5. REFERENCES

(1) Fowlkes, C.W., Montana Solar Data Manual, available from Montana Department of Natural Resources and Conservation, Helena, MT 59601.

(2) Balcomb, J.D., Hedstrom, J.C. and McFarland, R.D., "Simulation Analysis of Passive Solar Heated Buildings- Preliminary Results", LA-UR-76-1719, LASL, Los Alamos, NM.

(3) Balcomb, J.D. and McFarland, R.D., "Simulation Analysis of Passive Solar Heated Buildings-The Influence of Climate and Geometry on Performance", LASL, Los Alamos, NM.

(4) Roach, F., Noll, S. and Shaul, B.D.,"The Comparative Economics of Selective Passive Solar Designs in Residential Space Heating Applications", LASL, Los Alamos, NM.

(5) Taylor, H.E.,"A Microprocessor Monitoring System For a Solar Energy Installation" Conference on Performance Monitoring for Evaluation of Solar Heating and Cooling Systems, Washington, D.C., April 4, 1978.

6. APPENDIX: INSTRUMENTATION

A.1. TRS-80 Data Acquisition System

The data acquisition and processing requirements for solar performance monitoring are best satisfied by a computer-based system programmable in a high level language. Due to budget limitations we developed our own system using the mass-produced Radio Shack TRS-80 with 4K memory and Level II BASIC. This unit sells for about $700 and includes a cassette tape for storing programs and data. We developed two main accessories for this unit: a battery operated power supply and an analog/digital interface, Figure A1.

The power supply contains circuitry to continuously charge a conventional 12v lead-acid car battery when 110 vac power is available. Additional circuitry converts the battery voltage into the voltages necessary to power the computer and the A/D interface. A small battery is suffioient to power the system for about 5 hours during a utility outage.

The A/D interface incorporates a front panel with plugs for connecting the transducers, a signal conditioning board, an A/D interface board and a real-time clock with month, day, hour, minutes and seconds (5). The system accepts 40 transducer inputs: 1 solar insolation, 2 electric power, 5 status switches, 8 pulsed inputs (flow meters), 8 averaging temperature inputs (3 probes each channel) and 16 single probe temperatures. The signal conditioning and transducer power supplies are integrated into the chassis. Analog voltages between 1 and 4 volts are converted into a 12 bit number giving a resolution of about 1 mv.

The data acquisition is structured with a program written in BASIC. The inputs are

scanned, the voltages converted to the desired parameter using calibration constants and equations in the BASIC program and the current data displayed on the video screen. Averaging and/or other data processing is then executed and the clock is read. At the end of the averaging period, specified in BASIC, the data is written onto cassette tape.

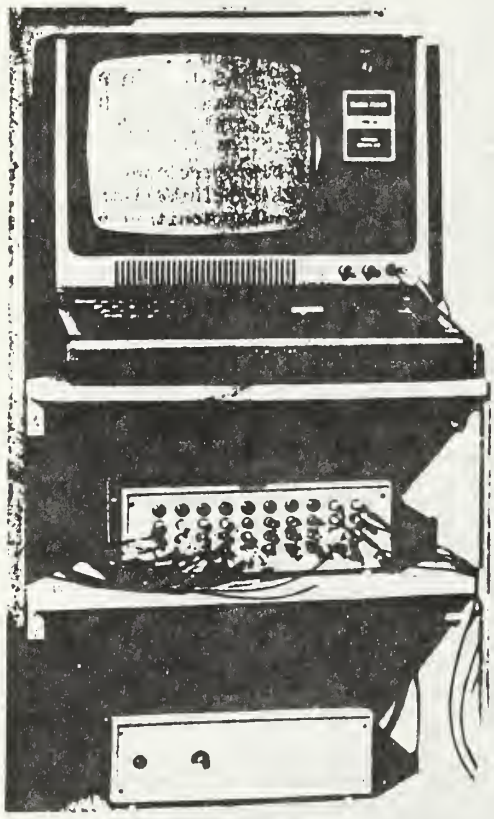


Fig. A1: TRS-80 Data Acquisition System

The system used for monitoring the passive house completed about 700 scans per hour and wrote hourly averages on the tape. Each side of an audio quality tape held about 11,000 numbers. Data on these tapes were transferred to diskette for processing on a larger computer. We have been using three of these TRS-80 data acquisition systems for 5 months to monitor a variety of solar heating projects.

A.2. Transducers and Accuracy

Temperatures were measured using the AD-590 made by Analog Devices. A computer program is used with the data system to calibrate the probes. The absolute accuracy of the temperatures was better than 1° C while the accuracy of small temperature changes was at least 0.1° C.

The solar transducer was positioned behind the glazing in the center of the solar wall to measure actual solar input to the storage wall. The transducer, based on a silicon cell, has been referenced to the NOAA standard and has an accuracy of 5%. Electric power input was monitored by measuring the current in the input mains with a clamp-on ammeter. This transducer is calibrated on-site using a watt meter and has an accuracy of at least 3%. The status inputs used a switch or relay to record the status of the fan and the insulating curtain.

The furnace input was determined from the temperature difference in the supply and the return air ducts and the flow rate. The accuracy of this measurement is assumed to be 10%. Air leaks located beyond the measurement station could further increase the uncertainty of the actual furnace power input. The weight of wood burned in the auxiliary furnace was determined to within 5%.

A total of 27 temperature probes were used. Four sets of three temperature probes were immersed in the water in the centers of the heat storage tubes. These probes were placed at varying levels in an attempt to compensate for stratification and to arrive at an average storage temperature. The temperature change in the tubes is on the order of 1° C per hour. A temperature differential of 5° C may exist between the top and the bottom of a tube at any given time. Analysis of the data showed that short term average power calculations were noticeably effected by the location and number of temperature samples. Daily average power calculations, however, were relatively independent of the probe locations.

16 copies of this public document were published at an estimated cost of $9.25 per copy, for a total cost of $148.00, which includes $148.00 for printing and $.00 for distribution.